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A Continuous Stirred Tank Reactor (CSTR) System for Exposing Plants to Gaseous Air Contaminants

Principles, Specifications, Construction, and Operation

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A Continuous Stirred Tank Reactor (CSTR) System for Exposing Plants to Gaseous Air Contaminants

Principles, Specifications, Construction, and Operation

By Walter W. Heck, Robert B. Philbeck, and John A. Dunning[1]

ABSTRACT

The continuous stirred tank reactor (CSTR) system utilizes a dynamic, negative-pressure, single-pass airflow for maintaining plants in a uniformly mixed exposure chamber (reactor) to study their response to gaseous air contaminants. Uniform mixing within the chamber is kept constant, regardless of inlet air velocity, by a 135-r/min impeller. Dispensing units, by means of rotameters and flow dilution for gases or calibrated syringe pumps for liquids, maintain constant gas concentrations within the chambers. The dispensing and chamber units are integrated with a shared-time monitoring unit for determination of gas (vapor) concentrations within the chambers. Rates for gas uptake, net photosynthesis, and transpiration can be determined by monitoring inlet and outlet gas streams. CSTR systems for use in environmental growth rooms utilize chambers designed for control of temperature, humidity, and light. CSTR systems for use in a greenhouse do not have environmental controls, but they do have high-intensity lamps so that a minimum light intensity can be maintained. Minor design modifications should permit use of the CSTR systems in the field. Performance data suggest that the CSTR design is superior to other chamber systems presently used for controlled exposures of vegetation to air pollutants. KEYWORDS: air pollution, continuous stirred tank reactor, gases, ozone, photosynthesis, phytotron, plant respiration, plants, plant transpiration, vapors.

INTRODUCTION

The effects of air contaminants on vegetation have been studied by means of a variety of exposure-chamber systems. Early exposure chambers were primarily recirculating (or partially recirculating) designs or small greenhouses modified for exposure studies (Setterstrom and Zimmermann 1938; Hill et al. 1959; Menser and Heggestad 1964; Hill 1967; Cantwell 1969; Berry 1970). More recent chambers have utilized many of the basic design features of the continuous stirred tank reactor (CSTR) system (Rogers et al. 1977), but these chambers were square or rectangular and relied upon airflow rate or pressure change instead of an impeller for mixing introduced pollutants (Heck et al. 1968). Dispensing of pollutants (gases) has been direct from bottled gas tanks or by means of a number of gas-handling techniques. Pollutant monitoring has normally required one instrument per chamber. Certain basic design features of the system discussed in this paper have been reported (Rogers 1975; Rogers et al. 1977). A similar dispensing and monitoring technique for ozone has been developed for open-top field chambers (Heagle et al., in press). An automated system for dispensing and monitoring chemicals for materials research (Spence et al. 1975) could be modified for use in vegetation studies. However, the system presented here is more flexible and less expensive.

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PRINCIPLES FOR A FUNCTIONAL EXPOSURE SYSTEM

The design of an exposure system should permit monitoring of environmental conditions during exposures. Environmental conditions should be close to those under which the plants are grown (greenhouse), or they should be controllable (growth chambers). Exposure-chamber design should consider airflow characteristics, the gases to be used, and the degree of environmental control desired. System versatility combined with simplicity should be a major consideration.

The system should be fabricated from materials having low adsorption characteristics to avoid possible reactions with introduced chemicals. Such side reactions could give incorrect uptake data, or they could produce secondary products that may cause plant injury not directly related to the toxicant being studied. If the test chemicals adsorb on chamber materials, lines and chambers should be cleaned or replaced before other chemicals are used.

Dynamic air systems are either negative-pressure or positive-pressure. The negative-pressure system eliminates the potential hazard of toxicant release into the area in which the exposure system is situated (for example, a greenhouse) and is preferred in all but field exposure facilities.

Dispensing lines should be chemically inert and heat resistant to allow the use of liquids in the vapor phase for the tests. The test chemicals should be introduced into the inlet duct in a dilute form. The duct should be designed to receive several test chemicals and aid in mixing the inlet air with the chemicals (gases) prior to entering the chamber. Air movement in the chamber may be laminar or turbulent. The design for a laminar flow system is exacting because plants in such a chamber interrupt the laminar flow and cause a modified turbulent flow (Hill 1967).

Air can be recycled at various ratios, or a single-pass system can be used. Recycled air may cause corrosion and particle buildup on air-handling equipment. Test chemicals may interact with components of the air-handling equipment to form injurious products. A single-pass system eliminates these problems. It also simplifies chamber design and may simplify control of both pollutant concentration and environmental conditions.

The desirable degree of environmental control depends upon the purpose of the experiment. Where chambers are used under natural light without supplemental lighting, exposures should be made only on high-intensity days (light greater than 15 klx), unless environmental variations are part of the experiment. An exposure system should be usable in the field, in the greenhouse, or in controlled-environment plant-growth rooms (such as a phytotron).

When comparisons across experiments are desired, exposures should require environmental control. Although greenhouse conditions often suffice, a minimum light intensity and day length must be controlled in most geographical locations. The development of exposure facilities to include environmental control can be obtained in several ways: by the use of a conditioning plenum on the inlet side of one or more exposure chambers, by placing the chamber into a controlled environment room, or by a combination of both.

Simplified construction and a common air-handling unit allow the use of a number of chambers in parallel without reducing the utility of the specific chamber design.

The continuous stirred tank reactor (CSTR) has been widely used in chemical engineering, and theoretical discussions of the CSTR concept are available (Jeffries et al. 1976). Recent applications of the CSTR chamber (reactor) in our laboratory by Rogers and associates (1975, 1977) have shown that these chambers meet the above design criteria. The CSTR chambers utilize the concept of ideal and instantaneous mixing of components entering the chamber with components present in the chamber. The gas concentration at the chamber exhaust should be epresentative of the concentration in any ortion of the chamber proper.

CSTR DESIGN AND CONSTRUCTION

The CSTR system is in use in our greenhouse nd controlled-environment [Phytotron (Downs nd Bonaminio 1976)] facilities for exposing lants to known concentrations of individual or nultiple pollutants. The system employs a polutant (gas) dispensing unit for control of the est chemical(s), CSTR exposure chambers, and shared-time gas-monitoring unit. Components or the greenhouse and Phytotron systems are letailed in the appendix (tables A–1, A–2, A–3).

OLLUTANT (GAS) ISPENSING UNIT

The dispensing unit (figs. 1 and 2 for the hytotron) has three components: (1) a source f gas or pollutant [high-pressure tank(s), an zone generator, or liquid chemicals], (2) preision rotameters, and (3) an air-dilution comonent (air manifold). Teflon tubing (TFE) is ised throughout this unit (0.25-in-o.d. by .19-in-i.d.).

Sulfur dioxide and most other gases are available in cylinders at low concentrations in an inert arrier (usually N_2). Desirable tank concentraions may be computed from the system flow ate, the exposure-concentration ranges, and the otameter ranges. The source gas is taken hrough a two-stage regulator, followed by a lowressure "pancake" regulator, into an aluminum gas) manifold where it is maintained at 5 lb/in^2. he test gas can be diluted with charcoaliltered air (shown for ozone but not for other ases in fig. 2) before it reaches the dispensing otameters.

Ozone is produced by passing dry O_2 (99.5 perent tank O_2) across a constant electric-discharge nit (ozone generator). The O_3–O_2 mixture flows nto an aluminum manifold where it can be diuted with charcoal-filtered air from the air nanifold. The ozone is dispensed through the lispensing rotameters. The rotameter settings re pressure dependent, requiring a stable presure within the ozone manifold. Stable pressure s provided by routing some flow from the ozone nanifold through a sealed cylindrical glass reservoir (18- by 2-in) filled to a specified height with water. The pressure is varied by changing the height of the water column. Stability is insured by exhausting some of the mixture through the water column. Airflow through the glass reservoir can be adjusted with a flow-rate control valve that bypasses the glass reservoir and reduces the rate of bubbling through the water column. The excess ozone exhausts to the building exhaust.

Liquid organic chemicals with moderately high vapor pressures at 25° C (for example, aniline and acetic acid) are dispensed by means of a calibrated syringe pump (Sage model 355) (fig. 3) (Cheeseman et al., 1978, unpublished data). The liquid is dispensed up into a glass mixing bulb maintained at 70° C with heat tape to assist in vaporization. The rate of injection at 25° C is determined by the following equation:

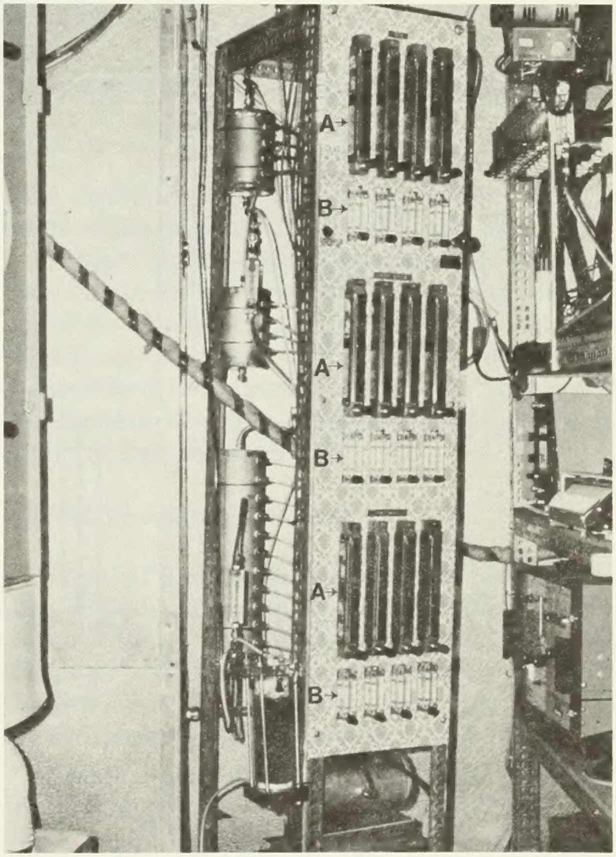


FIGURE 1.—The gas-dispensing unit for the four-chamber Phytotron CSTR system. The face of the unit shows the rotameters (A) that control the flow of the test chemicals and the rotameters (B) that control the dilution air. The greenhouse unit is similar but services nine chambers.

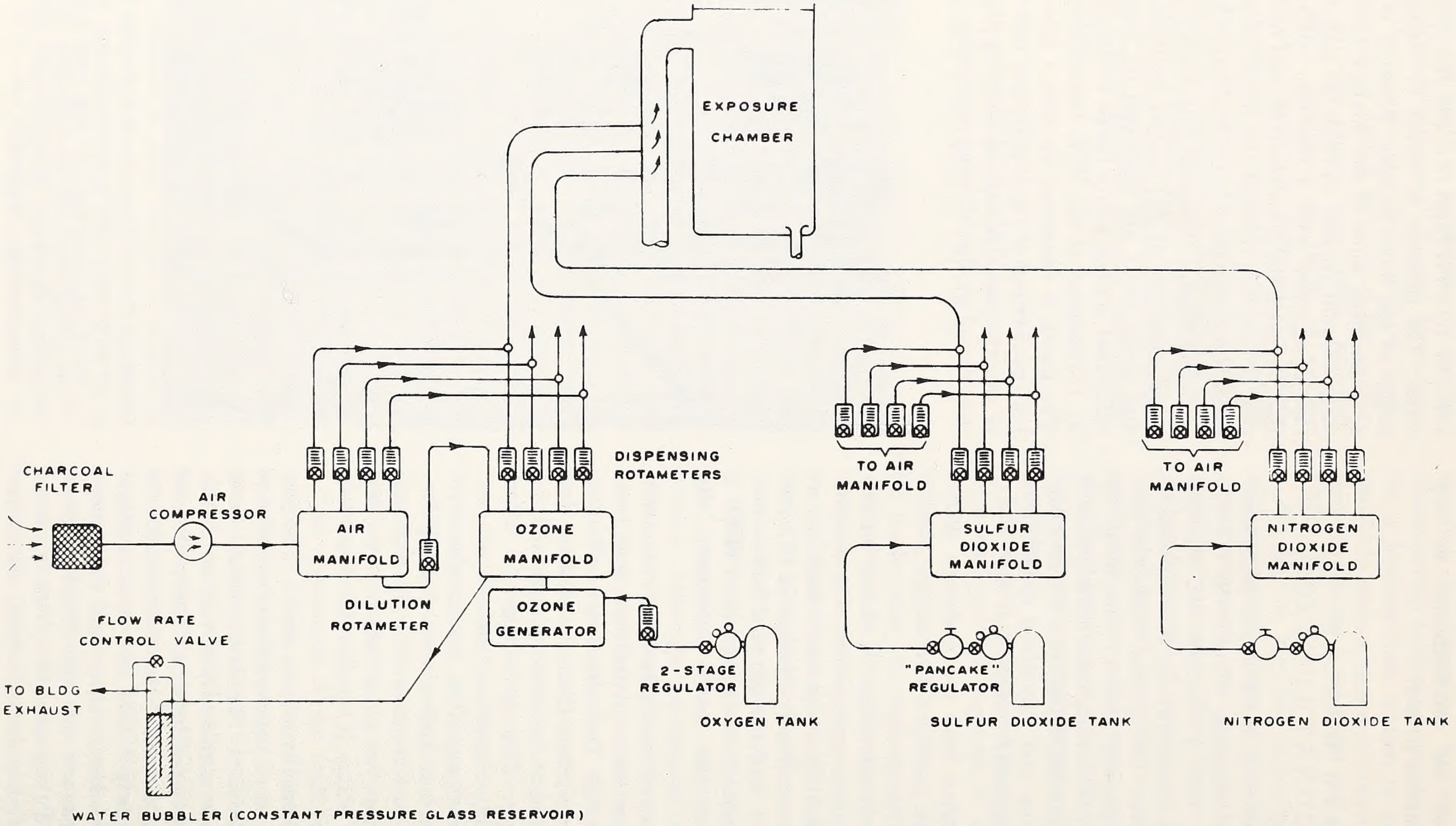


FIGURE 2.—Schematic of the gas-dispensing unit for the four-chamber Phytotron CSTR system. The greenhouse unit is similar but services nine chambers.

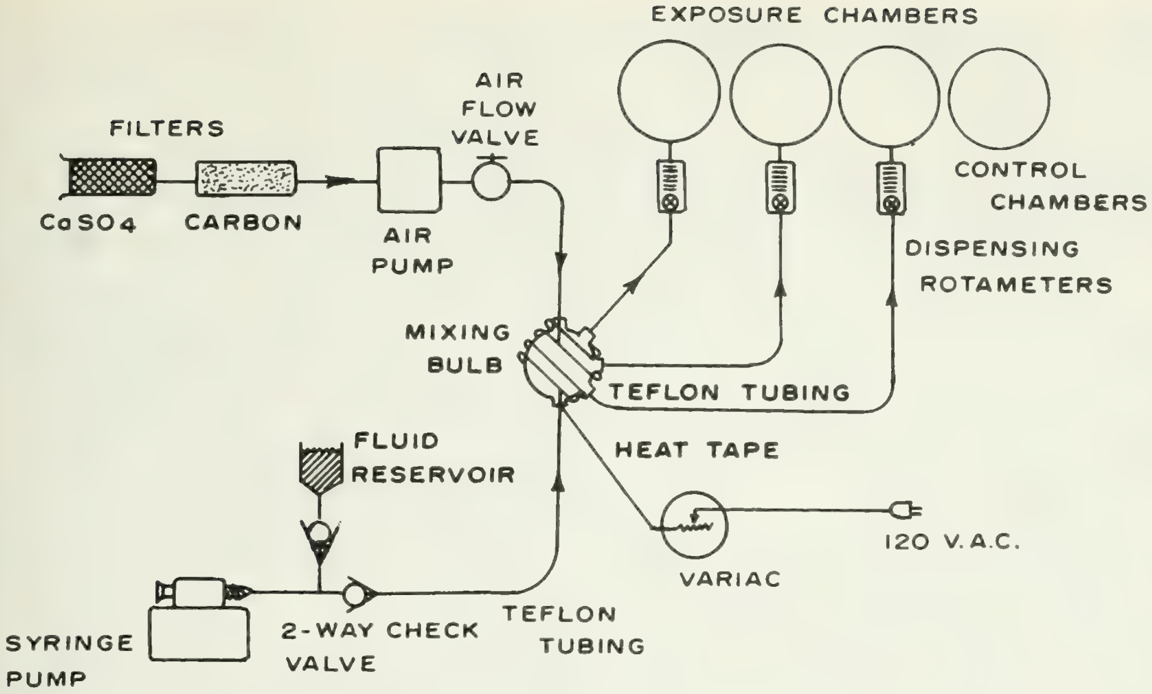


FIGURE 3.—Schematic of the liquid-dispensing unit that is incorporated into a set of greenhouse CSTR chambers.

$$\mu = F \times \frac{\mu l/l}{22.4} \times \frac{m}{\rho} \times \frac{273}{298} \times 10^{-3}, \qquad (1)$$

where μ=rate of liquid injection (ml/min), F=rate of airflow through the chamber (m^3/min), μl/l=microliters per liter of vapor desired in the chamber, m=molecular weight of the compound, and ρ=density of the liquid. Dry, charcoal-filtered air is delivered downward in the mixing bulb onto the fluid inlet. Airflow into the bulb is regulated by a valve to prevent excessive pressure. The chemical vapors (gases) are delivered through the dispensing rotameters to the exposure chambers. If more than 5 ml of fluid is needed for an exposure, a 50-ml syringe reservoir is connected by a two-way check valve to the syringe pump.

The dispensing rotameters are precision units calibrated to deliver 10 to 460 cm^3 air/min. The flow rates are controlled by 15-turn precision needle valves. These components have permitted consistent and reproducible flow rates for control of test gases (vapors) to the CSTR chambers.

The flow of all test chemicals may go through a secondary dilution component. The dilution air from the air manifold (fig. 2) moves the test chemical more rapidly to the chamber inlet duct and enhances final mixing by insuring that a more dilute mixture enters the inlet duct.

These pollutant (gas) dispensing units permit the injection of constant and reproducible amounts of one or more test chemicals into the CSTR exposure chambers. The basic design can be modified for automatic dispensing that could be controlled by the shared-time gas-monitoring unit (Spence et al. 1975).

CSTR Exposure Chamber

The CSTR exposure-chamber unit presently in use in both our greenhouse and Phytotron systems utilizes a dynamic, negative-pressure, single-pass airflow design, and several gases (pollutants) can be injected at once. Simplicity of design permits easy installation of a number of chambers into a single air-handling component with individual controls for each chamber. Figures 4 and 5 show the greenhouse chambers; figures 6 and 7 show the Phytotron chambers. Preliminary performance data suggest that airflow, gas mixing, and environmental conditions within the chambers are uniform. After the chambers were operational, all air leaks were calked prior to experimental research.

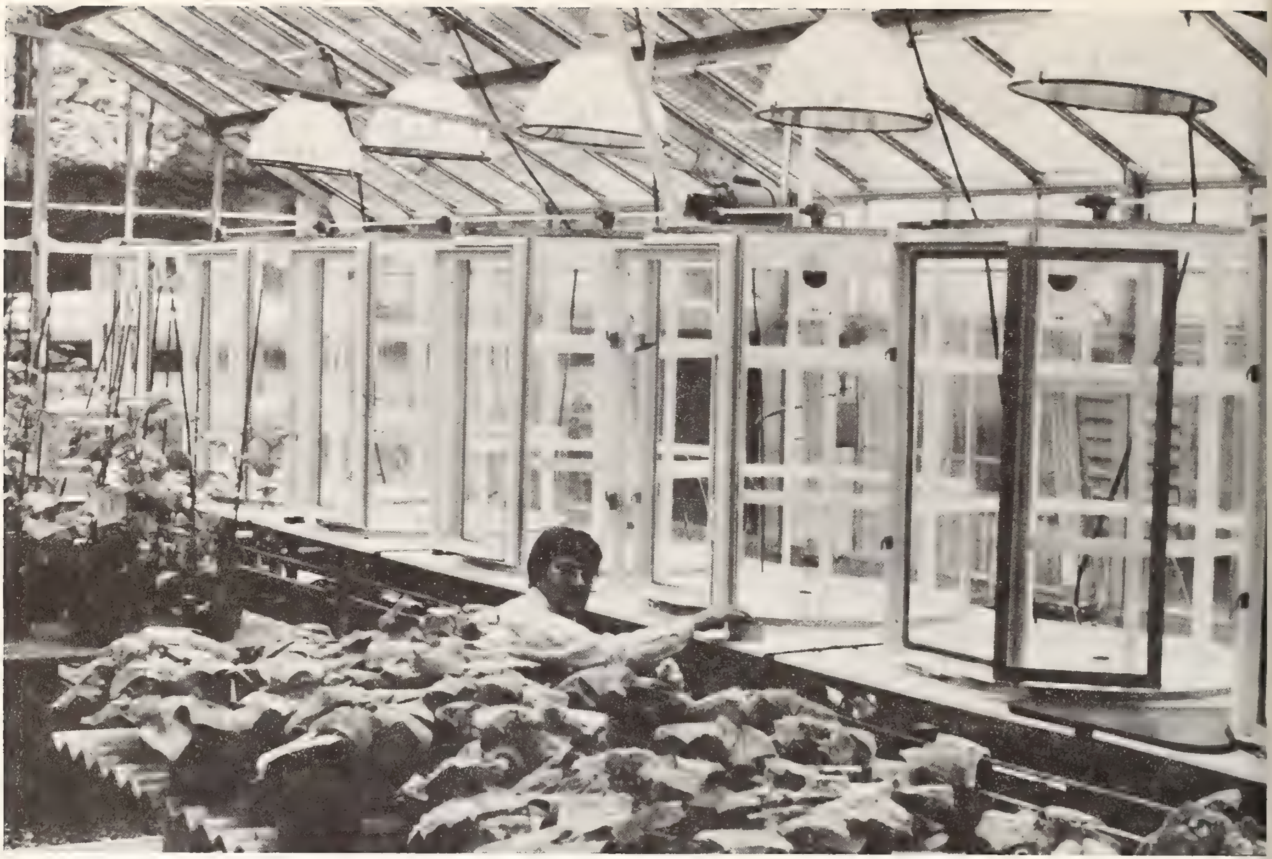


FIGURE 4.—The nine-chamber greenhouse CSTR system with supplemental lights (six chambers shown).

General construction

The nine-chamber CSTR system (fig. 5) in the greenhouse utilizes a single air-handling design. The four-chamber CSTR system (fig. 7) in the Phytotron uses a common exhaust manifold with one air inlet for two chambers. Construction details for the two chamber systems and flow characteristics and performance data are similar. Ideal CSTR dimension ratios of diameter to height are 1 to 1, but 1 to 1.5 is within acceptable limits. The greenhouse chambers are 42 by 48 in (1 to 1.14), and the Phytotron chambers are 32 by 54 in (1 to 1.7). The Phytotron chambers are slightly outside the technically acceptable limits for a CSTR but were designed to meet plant size and space constraints. Because of their unique features and their use in precision work, the Phytotron chambers (fig. 8) are discussed in detail below. The greenhouse chambers are similar in basic design (fig. 9).

The chamber frame (fig. 8) is constructed of three angle-iron uprights held together by top and bottom circular hot-rolled steel strips. Center strips butt to either side of the centered angle-iron framed door that was designed to affect minimally the circular nature of the chamber. The frame is mounted on a ¾-in-plywood base. The door is attached by two butt hinges and secured with two metal latches to provide rapid access to the chamber. An inlet-duct support plate was installed in the upper-rear position at the level of the impeller, and an exhaust opening was made in the floor near the door. A metal plate installed centrally on the metal top supports holds the impeller assembly. The CSTR concept calls for three vertical baffles at equidistances around the chamber to insure turbulent mixing. The angle-iron chamber supports act as narrow baffles and do increase turbulence.

All components of the chamber frame were sealed with a silicone grease to prevent air leaks. The frame was coated with an epoxy primer undercoating and with two coats of white epoxy paint. The frame was covered with 3-mil transparent Teflon (FEP) film. The film was secured

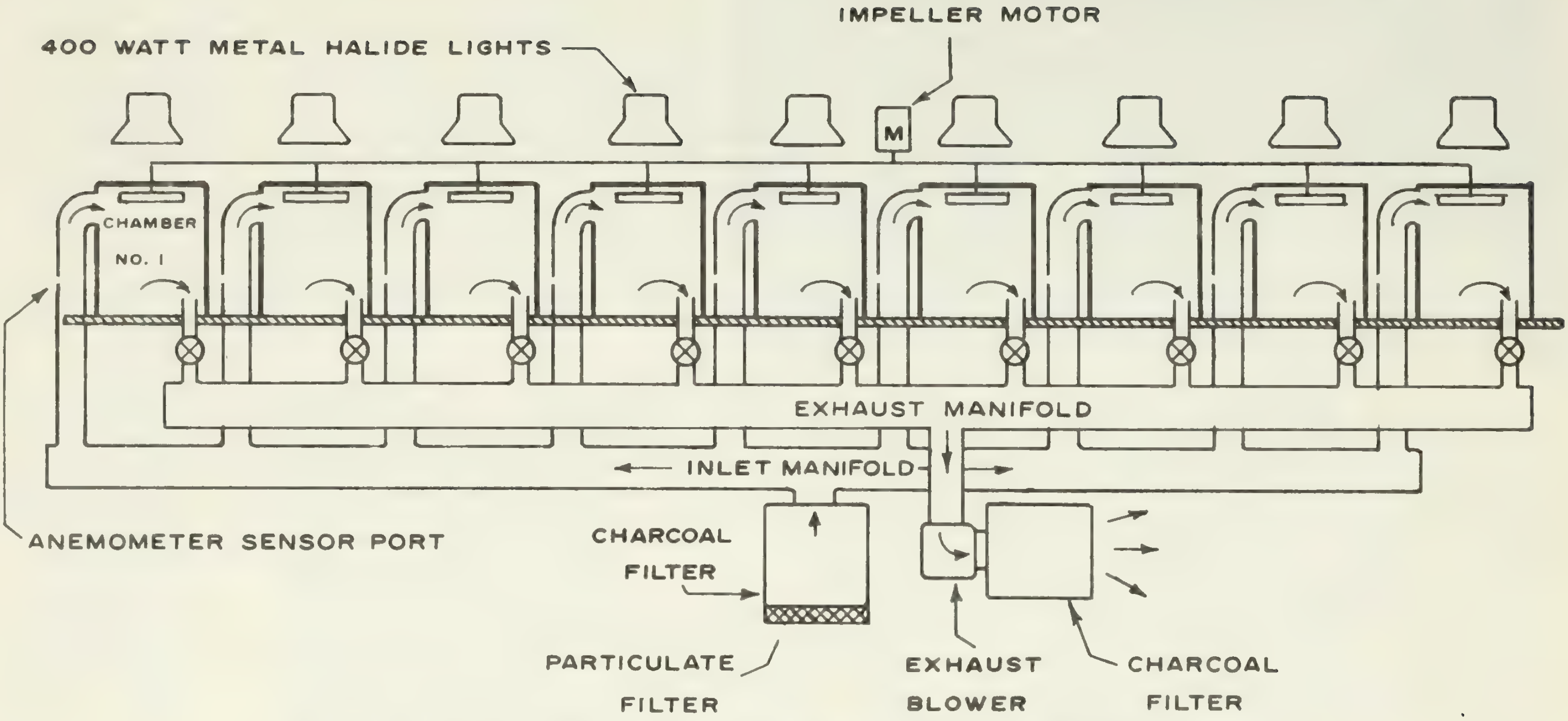


FIGURE 5.—Schematic of the nine-chamber greenhouse CSTR system with associated components.

over the frame by clamps (fabricated of stainless-steel strips and radiator clamps) located around the top and bottom support strips. An open-cell vinyl-foam gasket was cemented to the inner side of the clamps for assistance in film securement and film protection. The film was sealed at the door frame with vertical aluminum channels (open-cell vinyl-foam gaskets on inner surfaces). The channel was attached to the door frame with three sheet-metal screws. The top was covered with the Teflon film, secured with the same metal clamp used for the chamber film, and sealed around the impeller plate with Pliobond. The door was covered with the Teflon film and sealed to the door frame with Pliobond. The epoxy paint and Teflon film were used because these materials are highly inert to reactive chemicals.

The chambers (figs. 8 and 9) were fitted with attachments: a 3-in-diameter opening on the metal inlet plate of the Phytotron chambers (4 in for the greenhouse) accommodates the inlet duct; a ¾-in-diameter opening in the top is for the impeller shaft that supports a six bladed, 14-in diameter impeller with 3-in-wide blades in the Phytotron chambers (17.5-in diameter in the greenhouse); a 2-in-diameter opening in the floor is for the exhaust duct; and a plate with a Swagelok connection is attached close to the inlet duct to hold a sampling line to monitor the inlet air. The impeller shaft is sealed with a silicone grease.

The Phytotron chamber sides (exterior to the Teflon film) were covered with a thin aluminium sheeting coated with white enamel, which increased light intensity by 20 to 25 percent. This sheeting was covered with two 0.5-in-thick sheets of Rubatex insulation to help maintain chamber temperatures. The plenum boxes and inlet ducts were insulated with a single layer of the same material (fig. 8). The inlet manifold and ducts for the greenhouse chambers were also insulated with a single layer of the Rubatex to minimize temperature increases in the chambers on sunny days.

Air handling

The air-handling design for the greenhouse system is detailed in figure 5, and for the Phytotron system in figure 7. A high-pressure exhaust blower maintains 4 in of water negative static pressure in the exhaust manifold (3-in-diameter PVC pipe in the Phytotron, 6-in-diameter galvanized pipe in the greenhouse). Chamber exhaust feeders are 2-in flexible PVC hose in the Phytotron and 2-in aluminum duct in the greenhouse. All joints are sealed with a silicone grease to reduce air leakage. Each chamber exhaust feeder has a valve (ball valve in the Phytotron, butterfly valve in the greenhouse) for controlling airflow. This design maintains a negative pressure of 0.1 to 0.2 in of water in the exposure chambers at an airflow approximating one change every minute (24.5 ft^3 in the Phytotron, 37.7 ft^3 in the greenhouse).

A port for a hot-wire anemometer to measure airflow is located in the inlet duct. Air enters each chamber through an inlet duct (galvanized, 4-in-diameter pipe for the greenhouse; stainless-steel, 3-in-diameter pipe for the Phytotron) at a linear velocity of 432 (greenhouse) or 499 (Phytotron) ft/min with the one air change per min-

(*Continued on page 12.*)

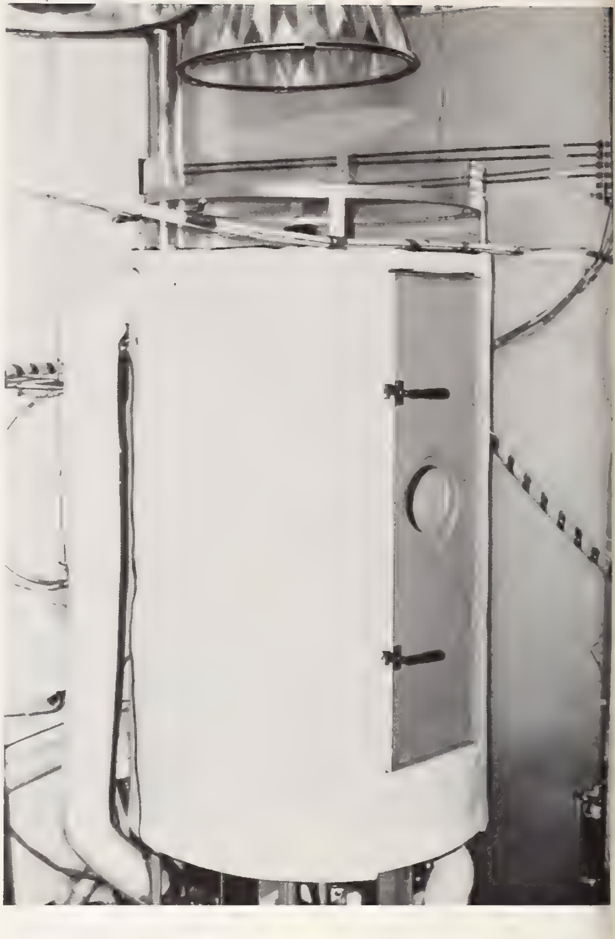


FIGURE 6.—A CSTR chamber (from the four-chamber Phytotron system), showing chamber insulation, water bath, and high-intensity lamp.

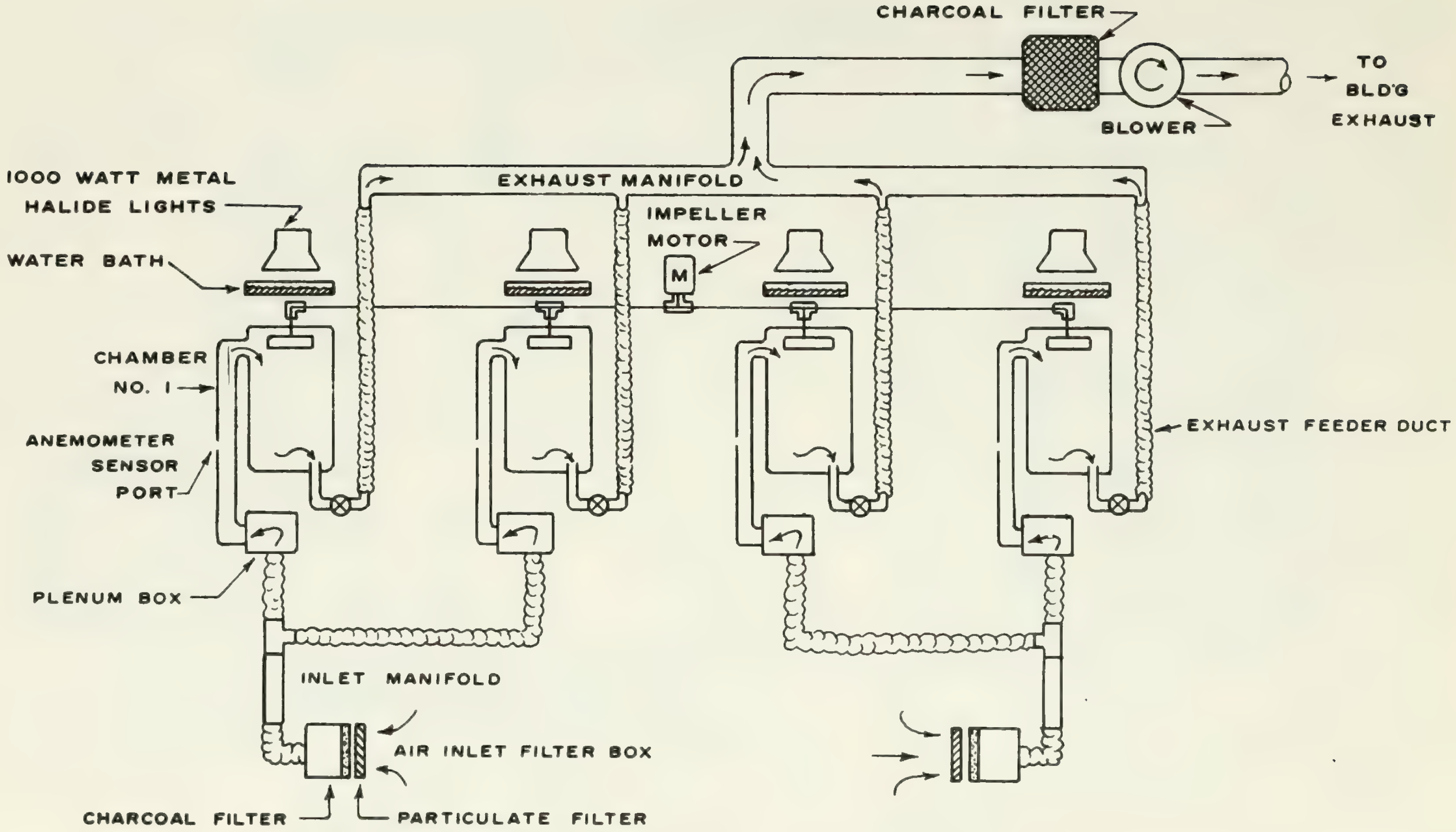


FIGURE 7.—Schematic of the Phytotron CSTR chamber unit with associated components.

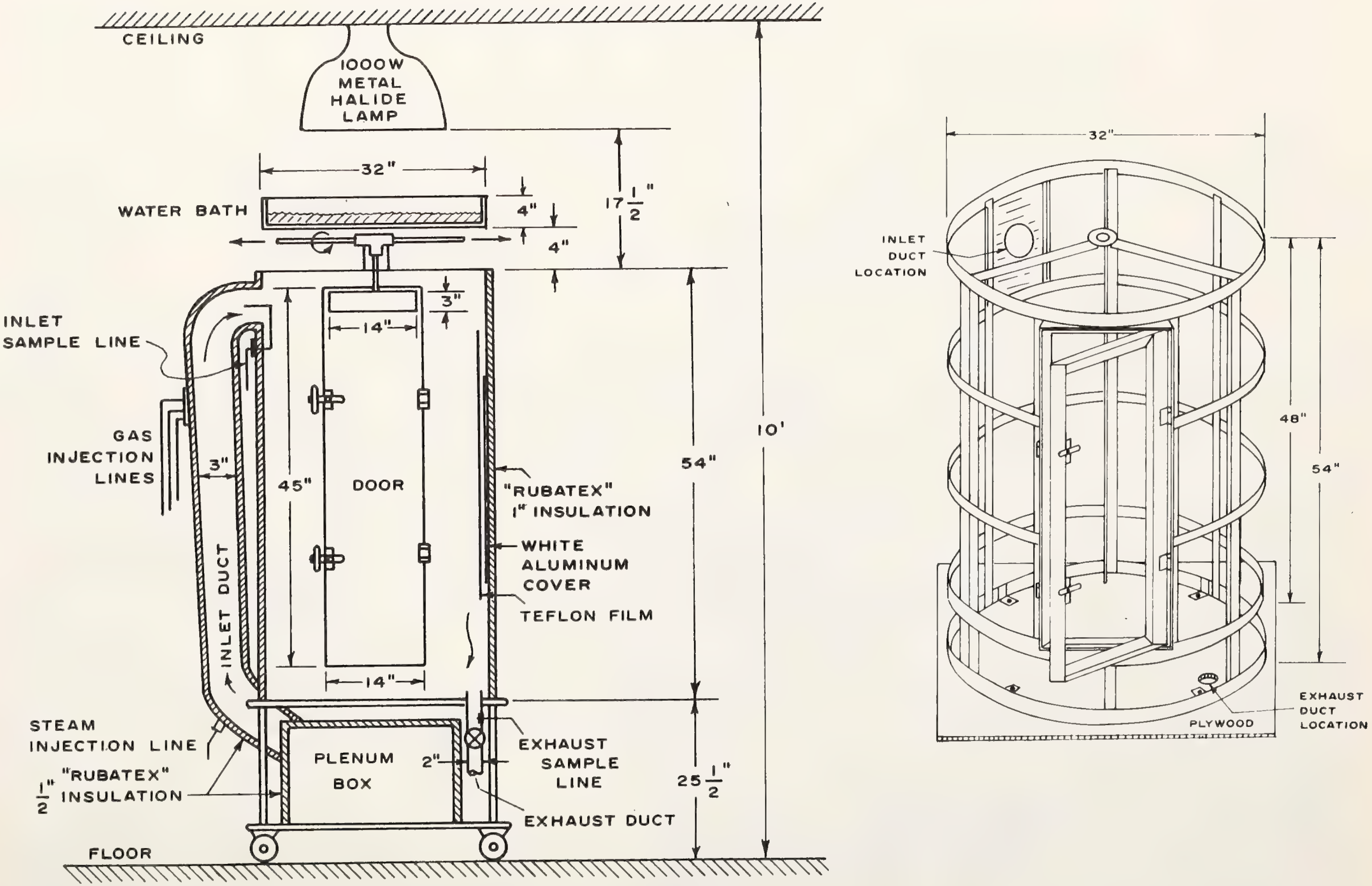


FIGURE 8.—Schematic of a single Phytotron CSTR chamber unit.

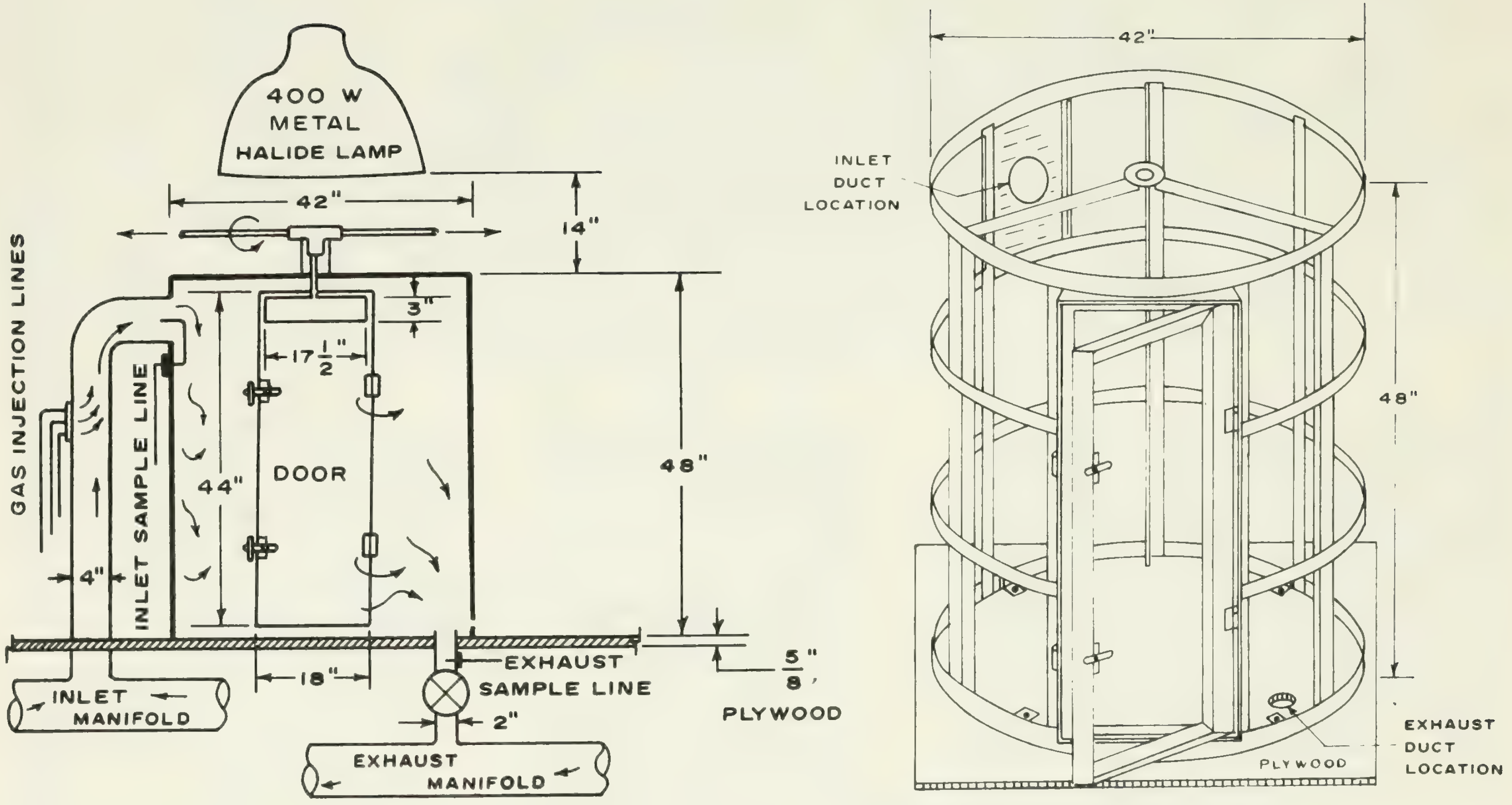


FIGURE 9.—Schematic of a single greenhouse CSTR chamber unit.

ute. This linear flow can be varied from 0.1 to 2 changes per minute, depending upon the experimental objectives, without affecting chamber mixing. "Instantaneous" mixing is maintained by the impeller (115 r/min in the greenhouse and 135 r/min in the Phytotron), which assures constant air movement throughout the chamber regardless of flow rate through the chamber.

Each Phytotron chamber has its own inlet plenum box for conditioning the air prior to entrance into the chamber. The plenum boxes of paired chambers are connected to a common particulate and charcoal filter located on top of the room containing the chambers. Air for the exposure chambers is drawn from an area containing a fairly uniform carbon dioxide concentration. The greenhouse-chamber inlets are attached to a common manifold equipped with a dust and charcoal filter for cleaning the airstream before it enters the exposure chambers.

Gas addition

Air contaminants (gases) are added through injection ports in the inlet ducts from the various dispensing systems (figs. 8 and 9). The contaminants are added in a highly diluted state and mix rapidly with the air in the inlet duct. Baffles in the inlet duct, above the injection ports, aid mixing of gases prior to entering the CSTR. Slight concentration gradients, if they occur, are immediately lost within the CSTR by impeller action. There are no specific limits to the number of test chemicals that can be added in the inlet duct, other than space limitations.

Lighting

Each Phytotron chamber has a 1,000-W high-intensity multivapor lamp (fig. 8) that gives an average light intensity of 35 klx at 60 cm above the exposure-chamber floor. The greenhouse chambers use 400-W lamps (fig. 9) to supplement natural light (about 15 klx). Both systems use faceted-type reflectors to provide more uniform light and a special glass shield on the bottom of the reflector to absorb most of the radiant energy. Each Phytotron chamber has a circular Plexiglas water bath (4 in above the chamber) to adsorb additional radiant energy and for use in light-quality studies. For routine use, the water baths are seldom used.

Environmental control

Greenhouse exposure-chamber conditions (light intensity, temperature, and relative humidity) approximate the greenhouse conditions. On a cloudy day, these greenhouse environmental conditions may include low light (the chamber minimum is maintained by the high-intensity lamps), lower temperature, and higher humidity than on a sunny day. On a sunny day, the exposure chambers receive about 85 percent of the light intensity in the greenhouse, are 1° to 3° C warmer, and have approximately the same dewpoint temperature (lower RH). Where possible, each treatment within an experimental design should be represented at each exposure time. Variations in replications in the design, done over time, will reflect variations in the greenhouse environment. Experimental results then reflect the average environmental conditions.

The Phytotron chambers are housed in a 10- by 15-ft room where the temperature is controllable between 18° and 27° C (Downs and Bonaminio 1976). Each chamber has an inlet plenum for control of temperature, and a solenoid and needle valve for steam inlet control (humidity) (fig. 10). Temperature is controlled by a proportional controller to regulate the input of heat from rapid-response strip heaters. Refrigeration can be varied but is normally set by means of a six-turn gate valve to insure a given glycol flow and thus a given coil temperature. A small blower recirculates air within each plenum to assure sufficient air movement over the coils to prevent icing. Humidity is controlled manually by adding steam through an 18-turn needle valve into the inlet duct. A three-way solenoid valve is inserted between the control valve and the inlet duct to bypass the steam when the chamber doors are open. Steam goes into a bypass manifold and into a drain. The solenoid is manually controlled (toggle switch). Humidity is adjusted during chamber setup for a given experimental design. In practice, once set, humidity fluctuations are minimal. Steam is generated in an electric steam boiler by means of de-ionized water.

SHARED-TIME GAS-MONITORING UNIT

The shared-time gas-monitoring unit (fig. 11, for the Phytotron) has three components: the monitoring lines and sampling manifold, the con-

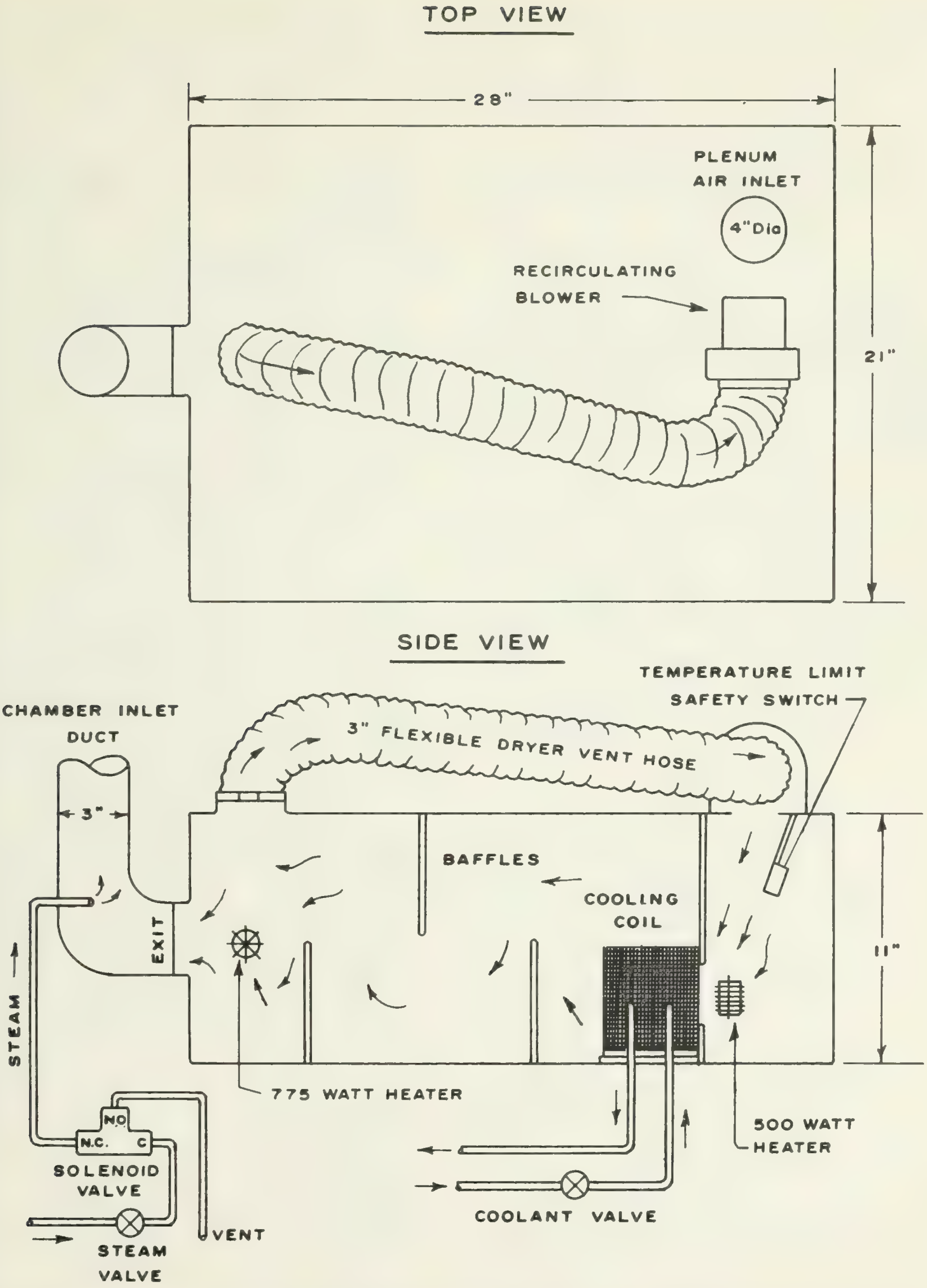


FIGURE 10.—Schematic of the environmental-control plenum box for the Phytotron CSTR chamber unit.

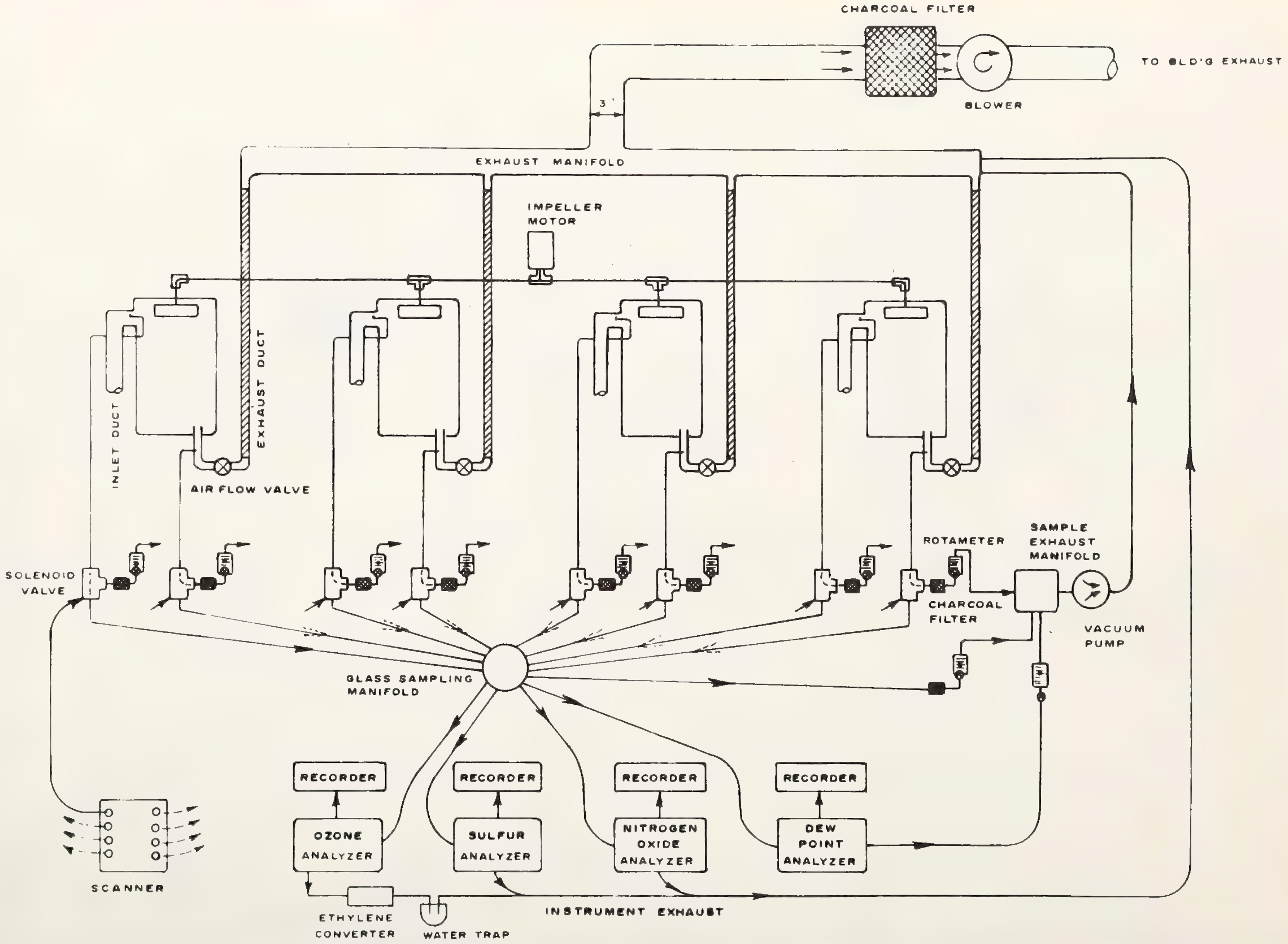


FIGURE 11.—Schematic of the CSTR system gas-sampling unit for the Phytotron. Note: All sampling lines and the sampling manifold are insulated and heat taped.

troller (scanner), and the monitoring instruments. These components are an integral part of the complete CSTR system and are basically the same for the greenhouse and the Phytotron systems.

Each CSTR chamber has an 0.25-in-o.d. Teflon monitoring line at the inlet and exhaust ports. These lines (about 30 ft in length for the Phytotron and about 40 ft for the greenhouse) run to the inlet ports of three-way stainless-steel solenoid valves that are close to the controller and instrumentation. The normally closed exhaust port of each solenoid valve is plumbed (0.25-in-o.d. Teflon tubing) to a glass sampling manifold. This manifold has additional ports for sampling lines leading to the monitoring instruments. When a given solenoid valve is energized by the scanner, the air sample is pulled through the glass sampling manifold by a stainless-steel bellows pump at a flow rate of 2 l/min. The air sample thus becomes available for analysis. The normally open exhaust port of each solenoid valve is plumbed (0.25-in-o.d. Teflon tubing) to the sample exhaust manifold. This manifold is under negative pressure adequate for a flow of 2 l/min from each sampling line. This rate permits continuous aspirations of samples through the sampling lines and into the solenoid valves, permitting a shorter sampling time. In the Phytotron system, all monitoring lines, solenoid valves, sampling lines, and the glass sampling manifold are wrapped with heat tape and kept at 30° C, or at least 5° C above chamber temperatures, so that no condensation will occur in the system. Lines to all instruments are insulated but not heat taped.

The controllers (scanners) are simple electromechanical stepping devices that energize the solenoid valves of the shared-time gas-monitoring unit. They are designed so that up to 20 lines in the greenhouse (8 in the Phytotron) can be routinely monitored on a rotating cycle. The time that a solenoid valve is energized is programed with a timing motor set for 2 min per sample line in both systems. In the Phytotron system, the eight sample lines can be scanned every 16 min or the four exhaust lines every 8 min, if only chamber concentrations are of interest. The nine-chamber greenhouse unit routinely scans the set of nine exhaust lines every 18 min.

The monitoring instruments for use in this system must have several characteristics: reliability, continuous analysis, fast response time (less than 1 min), less than 500 cm^3 sample airflow per minute, and an air pump that will work against a negative pressure. Each instrument is connected to the sampling manifold, and thus multiple analyses of each sample point are possible. Each instrument is attached to a recorder for continuous measurement. Each instrument exhaust is plumbed to the system exhaust manifold; the ozone instrument has an ethylene converter on the exhaust line. In our present system, we are monitoring ozone, sulfur dioxide, nitrogen dioxide, carbon dioxide, and dewpoint temperature. There are practical, but no theoretical, limitations to the number of points or the number of variables that can be monitored. Instruments are routinely calibrated using the most current methods (Hodgeson et al. 1972; Intersociety Committee 1972; U.S. Environmental Protection Agency 1976).

Temperatures are measured within the chambers with type T thermocouples attached to a 24-point temperature recorder. Each thermocouple bead is shaded by a small white cup to reduce the direct effects of radiant energy. Temperature can be measured in both the exhaust and inlets ducts. The exhaust duct is the best measure of the chamber air temperature. In certain designs, the exhaust and inlet temperatures must be monitored.

PERFORMANCE DATA

A CSTR system should be able to maintain uniform gas (contaminant) concentrations and environmental conditions throughout the chamber, and over time. The former is an indirect indication of chamber flow characteristics, and the latter is a measure of the stability of the pollutant (gas) dispensing unit and the environmental-control components.

Performance data were gathered to determine the degree of control (uniformity) both within and across the test chambers for several parameters: concentration of the test chemicals (gases), the environmental conditions, and the response of test plants. Sulfur dioxide and ozone were the test gases. Ozone was used because of its reactive nature; other gases should show an equal or better distribution pattern. Bush snap bean was used as the primary test plant because of its known sensitivity to the two gases. Environmental data are shown as mean values ± the

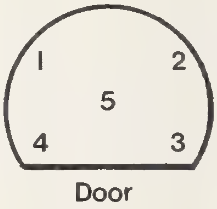
Table 1.—Ozone distribution within chambers, greenhouse CSTR system[1]

Sampling height[2] (cm)	Ozone concentration[3] (μl/l$\times 10^{-2}$)		
	Positions 1–4 (average)	Position 5	Mean
0.5	81.4±0.2	79.5	81.0±0.4
33	79.4±0.4	78.0	79.1±0.4
66	77.4±0.4	76.5	77.3±0.3
99	77.5±0.2	78.6	77.7±0.4
Mean	78.9±0.5	78.2±0.7	78.8±0.4

[1] Chamber 5 (center chamber) was used to test distribution within chambers; the chamber was empty and the O_3 concentration was stable before tests were conducted; greenhouse conditions were 24° C and overcast; chamber airflow was 1 change/min; the 400-W high-intensity multivapor lamp was on; each point was monitored for about 5 min to insure stable reading and the shared-time gas-monitoring unit was not used.

[2] Distance from the chamber floor.

[3] Chamber top view showing sampling locations and chamber door. Positions 1 to 4 were 15 cm from the side of the chamber and equidistant from each other. Position 5 is the chamber center. Mean values $\pm S_{\bar{x}}$ are shown when applicable.



standard deviation of the mean ($S_{\bar{x}}$). Plant response was evaluated by analysis of variance, and treatment means were separated by using LSD values at the 0.05 level of significance. In many cases, plant data also utilized the mean $\pm S_{\bar{x}}$.

Greenhouse System

Performance studies were conducted on the nine-chamber system for evaluation of pollutant distribution and sampling efficiency, temperature and light distribution within and across chambers, and plant response.

Pollutant distribution and sampling efficiency

Ozone was dispensed into the greenhouse chamber system, and distribution within the center chamber was monitored by means of a Monitor Laboratories chemiluminescent analyzer. Results of the ozone-distribution study are shown in table 1. Although small variations in ozone concentration are found across the chamber at a given height and vertically within the chamber, the data suggest that ozone uniformity is within the accuracy of the monitoring method. Similar tests with and without plants have duplicated these results. Our work shows that the exhaust concentration is representative of the chamber concentration. Routine monitoring should be done from the chamber exhaust port.

To test the shared-time gas-monitoring unit, we compared chamber ozone concentrations monitored directly and those monitored through the shared-time components (solenoid valves, sampling manifold, fittings, and additional lines). The results (table 2) show better than a 96±1 percent "sampling" efficiency across the nine chambers for ozone, indicating that monitoring by use of the shared-time system gives valid data for each chamber.

Environmental measurements

Chamber light intensity, temperature, and humidity are dependent upon the existing ambient conditions within the greenhouse. On cloudy or overcast days, the 400-W multivapor lamps, mounted over the chambers and used in all experimental work, supplement natural light. The chamber checkouts were done on cloudy days to determine chamber function under uniform greenhouse conditions. Greatest variability should be found under conditions of full sun on a hot summer day. Variations should be primarily across chambers rather than within chambers.

Results of a temperature-distribution study within a chamber showed both vertical and horizontal uniformity (table 3). The CSTR chamber

Table 2.—Shared-time sampling efficiency across chambers, greenhouse CSTR system

Chamber[1]	Sampling efficiency[2]
1	0.95
2	.95
3	.93
4	.96
5	.97
6	.97
7	.98
8	.99
9	.95
Mean	.96±0.01

[1] The probe was at 66 cm in position 5 (see table 1, footnote 3) for measurements in all chambers. General conditions were as described in table 1, footnote 1.

[2] The efficiency is the rate of the value obtained with the shared-time gas-monitoring unit divided by the value of directly monitoring the chamber. (Sample line length was the same.) The mean is $\pm S_{\bar{x}}$.

Table 3.—Temperature distribution within chambers, greenhouse CSTR system[1]

Height[2] (cm)	Average temperature[3] (°C)
0.5	26.7±0
33	26.7±0
66	26.7±0
99	26.5±0.1
Mean	26.6±0.04

[1] Chamber 5 was used to test temperature distribution within a chamber. The chamber was empty; greenhouse conditions were overcast, mean light intensity was about 10.8 klx; average chamber airflow was 0.835 change/min; inlet plenum of the chamber unit was 21.7° C.

[2] Distance from the chamber floor.

[3] Mean values $\pm S_{\bar{x}}$ across the 5 positions shown in table 1; thermocouples were exposed.

Table 4.—Comparison of inlet and exhaust temperatures across chambers, greenhouse CSTR system[1]

Location	Average temperature (°C)	
	Lights on	Lights off
Inlet	23.3±0.1	23.6±0.2
Exhaust	26.1±0.2	25.3±0.2
Exhaust increase	2.8±0.17	1.7±0.07

[1] Mean values $\pm S_{\bar{x}}$ across the 9-chamber system were taken with the 400-W high-intensity multivapor lamps on and off. Data were taken on a day similar to that described in table 3, footnote 1. However, values in the 2 sets of data (tables 3 and 4) are not comparable.

inlets are attached to a common manifold. No cooling or heating is associated with the manifold, and so the chamber temperatures and relative humidities (RH) are directly related to the greenhouse temperature and humidity. Chamber temperatures are also directly related to light intensity. On heavily overcast days (natural light intensity less than 2 klx), with the lights on, a small temperature increase (approximately 0.5° C) was found between the chamber inlet air and the chamber exhaust air. This difference was 1.7° to 2.8° C with increased natural light intensity (table 4). The inlet and exhaust temperatures across the nine-chamber system were within ±1 percent, with or without supplemental lights on a cloudy day. The temperature increase between exhaust and inlet was 1.7°±0.07° C without supplemental light and 2.8°±0.17° C with supplemental light. Full sunlight would have increased variations across the nine-chamber system and the differences between inlet and exhaust temperatures. The latter can reach 5° C on bright sunny days.

Light distribution is uniform both across and within chambers (table 5) on overcast days. When the supplemental lights are used, light variation at 18 cm within a chamber may be as much as ±6 percent, and across chambers as much as ±3 percent. Variations are greater at the 60-cm height and less with the lights off. The variations at 60 cm probably reflect shadow effects from structural parts of the chambers.

Across and within chambers, uniformity is enough so that average variations will not have a significant impact on plant responses.

Plant studies

Bush snap bean (*Phaseolus vulgaris* L. 'Spurt') was used to determine the uniformity of injury within and across the nine-chamber greenhouse system. Plants were seeded in 10-cm pots in a 4 : 2 : 1 mixture of Metro mix to soil to sand and thinned to one plant per pot at 7 d. Plants were watered daily with tapwater and fertilized after

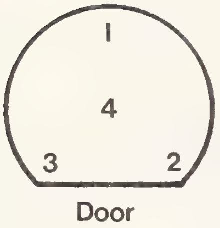
Table 5.—Light distribution within and across chambers, greenhouse CSTR system[1]

Chamber or position[2]	Chamber light intensity (klx)[3]			
	Lights on		Lights off	
	18 cm	60 cm	18 cm	60 cm
Chamber:				
1	14.6±0.95	18.9±1.5	8.5±0.2	8.7±0.1
2	16.0±0.5	19.1±1.6	8.6±0.1	8.9±0.2
3	13.8±0.8	16.4±1.9	8.4±0.3	8.6±0.1
4	14.5±0.9	17.5±2.3	8.0±0.3	8.4±0.2
5	14.9±0.6	17.1±1.8	8.3±0.2	8.5±0.1
6	15.3±0.6	18.8±0.9	8.3±0.3	8.6±0.2
7	13.2±0.65	16.2±1.5	8.0±0.3	8.5±0.2
8	14.0±0.45	17.2±0.8	8.0±0.2	8.5±0.2
9	15.2±0.7	18.9±1.3	7.8±0.3	8.1±0.2
Position:				
1	14.1±0.4	16.4±0.9	8.6±0.1	8.4±0.1
2	15.5±0.4	19.1±0.8	7.7±0.2	8.3±0.1
3	15.6±0.3	19.9±1.0	8.4±0.1	8.6±0.1
4	13.2±0.3	15.6±0.5	8.2±0.1	8.8±0.1
Mean	14.6±0.23	17.8±0.50	8.2±0.08	8.5±0.05

[1] The chambers were empty; greenhouse conditions were overcast (about 11.0 klx), about 27° C; measurements were taken in early morning.

[2] Positions 1–3 were 10 cm from the side of the chamber and equidistant from each other; position 4 is in the center.

[3] Lights were 400-W high-intensity multivapor lamps; distances are heights above the chamber floor. The values for chambers are mean values $\pm S_{\bar{x}}$ across the 4 positions; the positional values are means $\pm S_{\bar{x}}$ across the 9 chambers; the overall mean is the mean $\pm S_{\bar{x}}$ across and within chambers (36 points).



14 d with a solution of Peters 20–20–20 fertilizer. Plants were exposed to 0.20 μl/l O_3 for 2 h when they had one partially developed trifoliate leaf (14 d from seed, experiment 1) or two well-developed trifoliate leaves (21 d from seed, experiments 2 and 3).

The three experimental designs were run to test the uniformity of plant response across and within chambers. In the first experiment, 1 plant was placed at each of 20 positions in each chamber for a total of 180 plants, and the plants were exposed at 14 d from seed. The second experiment was similar except that the plants were exposed at 21 d from seed. In the third experiment, 1 plant was placed at each of 12 positions in each chamber, and the experiment was replicated for a total of 216 plants. These plants were exposed at 21 d from seed. Experiments 1 and 2 were done in October under good growth and exposure conditions. Experiment 3 was done in the spring under similar conditions. Percentage of foliar injury was determined (a 0–100-percent subjective index in 5-percent increments) 3 d after exposure for each expanded leaf on each test plant.

The data were difficult to analyze uniformly across experiments because of the variation in severity of effects. Because the primary purpose was to determine uniformity of response across and within chambers, data were used only from similar leaf positions where injury was between 10 and 90 percent. The first trifoliate leaves were used in experiment 1, the second trifoliate leaves were used in experiment 2, and the first and second trifoliate leaves were used in experiment 3.

Positional effects are not significant in the analysis of variance (table 6). The mean injuries $\pm S_{\bar{x}}$ are shown along with minimum and maximum values. A similar design with soybean [*Glycine max* (L.) Merr. 'Dare'] also showed no positional effects. Because experiment 3 had two replications, the chamber-by-position interactions were tested, and no interaction was found. No consistent positional effects have been noted in the results obtained to date. The chambers seem to function well as CSTR units.

Table 6.—Uniformity of foliar injury to snap beans from ozone within and across chambers, greenhouse CSTR system

Test unit	Experimental design[1]		
	14-d acute[2]	21-d acute—1[3]	21-d acute—2[4]
	POSITION[5]		
Probability $>F$	0.44	0.46	0.54
Mean (% injury $\pm S_{\bar{x}}$)	12.8±0.7	87.9±0.8	45.5±0.6
Min–Max (% injury)	8.3–17.2	78.3–93.1	43.8–49.7
	CHAMBERS		
Probability $>F$	0.42	0.95	[6]0.01
LSD at 0.05			5.1
Mean (% injury $\pm S_{\bar{x}}$)	12.8±0.7	87.9±0.5	45.5±2.0
Min–Max (% injury)	9.3–15.8	86.0–89.6	36.5–54.4

[1] The 1st 2 designs were run in October and 3d in the spring. The plants were exposed 1 time (at 14 or 21 d from seed) to 0.20 µl/l ozone for 2 h. LSD values are shown when treatments have significant F values.

[2] Injury to the 1st trifoliate leaf.

[3] Injury to the 2d trifoliate leaf.

[4] Average injury to the 1st and 2d trifoliate leaves across 2 replications.

[5] There were 20 positions in experiments 1 and 2, and 12 positions in experiment 3. These positions were equally spaced in the chambers.

[6] There was a significant chamber-by-replication interaction; however, chambers 3 and 7 gave lower injury values in both replications.

The response of snap beans across chambers (table 6) is significant for the third design but not for the first two designs. The third design also showed a chamber-by-replication interaction. According to the data for the chamber-by-replication interaction, some chamber variation shows up, but chambers 3 and 7 are consistently low over replications for both trifoliate leaves. This variation suggests a chamber effect that either depends upon external conditions or reflects some change in exposure concentration. The four runs (including each replication of experiment 3) were averaged for each chamber, and the results are shown in table 7. Chamber 7 was the only chamber that gave consistently low values, although in experiment 3 both chambers 3 and 7 gave consistently low injury responses. The soybean design showed similar responses across chambers except that chamber 1 was low. When all results are reviewed, no consistent pattern exists across chambers. Randomly picked chambers should be adequate for all experimental designs.

Table 7.—Uniformity of foliar injury to snap beans from ozone, average response across chambers, greenhouse CSTR system[1]

Chamber	Injury (percent)
1	47.1
2	50.9
3	43.5
4	49.6
5	48.2
6	52.3
7	43.3
8	48.6
9	47.8
Mean	47.9±1.0

[1] Chamber values were averaged across the 3 designs, and the overall mean $\pm S_{\bar{x}}$ was calculated.

PHYTOTRON SYSTEM

Performance studies were conducted on the four-chamber system for evaluation of airflows, CSTR performance, interaction of introduced pollutants, temperature-control limits, light intensities, and plant effects (snap bean).

Chamber airflows

Airflow velocities through each chamber inlet duct were measured with a hot-wire anemometer and were set (by means of the exhaust valve) to give a uniform flow. These velocities were divided by the calculated average airflow velocity (499

Table 8.—Airflows across chambers, Phytotron CSTR system[1]

Chamber	Airflow measurements (inlet)[2]		Gas-injection measurements (exhaust)[3]	
	Airflow velocity (ft/min)	Change per minute	Measured (μl/l)	Calculated (μl/l)
1	493	0.988	0.91	1.050
2	493	.988	.90	1.050
3	489	.980	.93	1.059
4	489	.980	.93	1.059

[1] The chambers were empty, the lights were on, and the temperature was 25° C.

[2] A hot-wire anemometer was placed in the center of the 3-in inlet duct to give maximum flow velocity for the equation: average flow velocity = 0.85 times maximum flow velocity. Airflow velocity through the inlet duct for 1 change/min in the 24.5-ft^3 chambers is 499 ft/min.

[3] Sulfur dioxide (about 1.0 percent in dry N_2) was injected (72 cm^3/min) into each chamber and monitored at the exhaust using a Meloy flame-ionization sulfur analyzer.

ft/min) to give the number of air changes per minute (table 8).

Sulfur dioxide was injected into each of the chambers as a secondary technique to confirm uniform airflows across chambers. An equal flow (72 cm^3/min) of sulfur dioxide gas (about 1.0 percent in nitrogen) was dispensed into each chamber, and the exhaust duct was monitored for approximately 20 min to assure steady-state conditions. The calculated sulfur dioxide concentrations were about 15 percent (0.137 μl/l) above the measured values (table 8). This difference probably reflects an error in the reported tank concentration (0.87 percent would give the same values) and some loss of sulfur dioxide within the chamber. Because the measurements were taken at the inlet (hot-wire anemometer) and at the exhaust (gas injection), the differences could reflect an air leak into the system. However, if air leaks exist, they must be small and uniform across chambers. The gas-injection measurement indicates a high uniformity of airflow across the four chambers.

Operation as a CSTR

Ozone buildup and decay curves were determined for the four Phytotron chambers without plants. At zero time, 45 cm^3/min of the ozone mixture was injected into each chamber. Concentrations were recorded each minute for 15 min at each exhaust port. The ozone flows were discontinued, and concentrations were recorded for the next 15 min. The ozone buildup and decay curves were almost identical for the four chambers. Only data for chamber 1 are shown (fig. 12). The first minute shows little buildup because of the delay inherent in the dispensing system. The theoretical curve for CSTR operations will take 6.6 chamber air changes to reach a 99-percent buildup or decay. At one change per minute it would take 6.6 min. The results shown in figure 12 suggest that the Phytotron chambers meet this design criteria and do respond as a CSTR. Other checks have shown about a 5-percent loss of ozone from inlet to exhaust in an empty chamber, possibly because of small leaks and sorption or reaction with wall surfaces. We believe that most of this loss resulted from the latter. Differences in inlet and exhaust concentrations with a plant load in the chamber may be as high as

Table 9.—Effects of the simultaneous addition of two pollutants, Phytotron CSTR system[1]

Test	Ozone concentration (μl/l)	Sulfur dioxide concentration (μl/l)
1*a*	0.615	0
	.615	0.628
1*b*	0	.718
	.570	.717
2*a*	.51	0
	.51	.66
2*b*	0	.66
	.51	.66

[1] Chamber 3 was used without plants at 26° C and full light. Gas concentrations were monitored at the exhaust port. In the *a* tests, ozone was stablized, then sulfur dioxide was injected, and both gases were measured. In the *b* tests, sulfur dioxide was injected, then ozone was added.

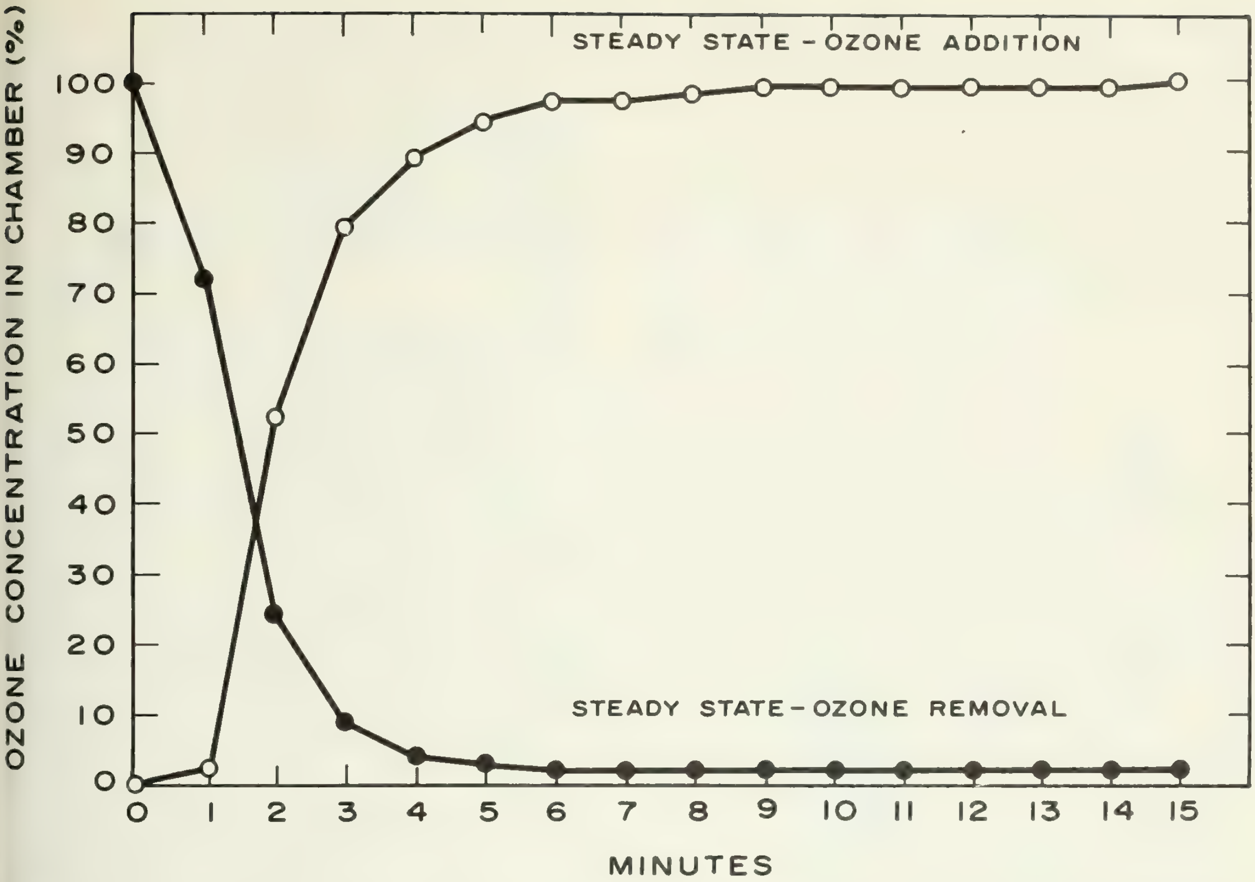


FIGURE 12.—Ozone buildup and decay curves from chamber 1 in the Phytotron CSTR system. Similar curves were found for the other chambers. No plants were in the chamber. The inlet concentration was about 0.40 μl/l and the equilibrium exhaust concentration was 0.385 μl/l (exhaust to inlet ozone ratio was 0.96). All data were obtained from the exhaust-monitoring port, which represents the chamber concentration. Chamber lights were on, chamber was 25° C, and airflow was 1 change/min (24.5 ft^3/min). The exhaust to inlet ozone ratio in other tests was 0.95 for empty chambers.

50 percent, and so the chambers are useful for gas-uptake studies.

Interaction of introduced pollutants

Ozone and sulfur dioxide (about 1.0 percent in nitrogen) were studied to see if they would react chemically in the chamber when dispensed simultaneously. We had found in earlier tests (unpublished data, 1967) that O_3 and SO_2 did not interact at the concentrations and the short chamber-residence times normally used. The tests were conducted in chamber 3 without plants and were repeated. Sulfur dioxide was first added to a steady-state O_3 concentration, and ozone was added to a steady-state sulfur dioxide concentration. Neither gas affected the concentration of the other gas in these tests (table 9).

Temperature control

A study was conducted to determine the degree and limits of control for chamber temperatures. Data were collected with the 1,000-W lamps on without plants in the chambers and with the plenum coolant turned on. Data are shown only for chamber 3 (table 10) because all four chambers were similar.

Chamber temperature control was set for maximum cooling, approximately 3 mm of water was added to the Plexiglas water bath, and the exposure-chamber room was set at about 65° F (18.3° C). After approximately 1 h of chamber operation, the room temperature stabilized at about 66° F (18.9° C), and the exhaust duct of chamber 3 stabilized at about 63° F (17.2° C). Chamber 3 was used to determine minimum temperatures when steam was added to give three

Table 10.—Temperature control, Phytotron CSTR system[1]

Test[2]	Chamber center (°C)	Exhaust[2] (°C)	Room (°C)	Chamber RH (%)	Water bath (mm H_2O)
1	18.9	17.8	18.3	55	3
2	19.4	17.8	18.9	74	3
3	19.4	18.3	18.9	90	3
4	20.0	18.3	18.9	90	0
5	40.6	38.9	25.0	35	0

[1] Chamber 3 was used without plants, with lights on, and with the plenum coolant turned on. Chamber 3 is representative of the 4 chambers.

[2] Tests 1–3 show effects of added steam (humidification). Tests 3 and 4 have the same inlet heat load, but the water bath is empty in 4. Test 5 has no steam, but heater controls were set for continuous operation to obtain maximum temperature.

Table 11.—Light distribution within and across chambers, Phytotron CSTR system[1]

Chamber	Chamber light intensity (klx) at—												
	[2]30 cm		[2]60 cm					[2]90 cm				[2]120 cm	
	Positions	Position	Positions	Position 5[3]				Positions	Position 5[4]			Positions	Position
	1–4	5	1–4	*a*	*b*	*c*	*d*	1–4	*a*	*b*	*c*	1–4	5
1	29.9±0.3	36.5	36.0±0.1	39.8	38.5	36.3	35.5	47.6±0.2	47.8	770	16.11	60.7±1.2	35.5
2	28.1±0.2	33.8	34.8±0.7	37.4	36.8	36.8	36.3	45.6±0.3	45.5	730	16.04	57.0±2.3	35.0
3	31.9±0.2	39.8	39.1±0.4	42.3	40.3	35.3	35.0	50.0±0.4	49.5	810	16.36	64.9±1.2	33.5
4	28.5±0.2	34.0	34.9±0.4	36.8	35.5	35.5	34.5	44.3±0.6	42.5	690	16.24	56.1±1.2	31.5
Mean	29.6±0.4	36.0±1.4	36.2±0.5	39.1±1.3	37.8±1.0	36.0±0.3	35.3±0.4	47.1±0.3	46.3±1.5	750±25.8	16.19±0.07	59.7±1.2	33.9±0.9
1[5]	30.6±0.4	37.8	37.2±0.3	41.3	...	...	...	48.1±0.3	...	...	...	61.6±1.5	37.0

[1] The chambers were without plants, at 26° C, with full light, and no water in the water bath. Positions 1–4 are 10 cm from the side of the chamber; position 5 is centered (see table 1).

[2] Distance from the chamber floor.

[3] The readings were taken at different times to show normal variation in intensity. The *c* and *d* readings were adjusted by means of a 7-in disk on the chamber 3 lamp reflector shield and a 6-in disk on the chamber 1 lamp reflector.

[4] Photosynthetically active radiation (PAR) light energy in microeinsteins ($m^{-2}s^{-1}$) (*b*) was measured for the 90-cm height in the 4 chambers at position 5 and compared with kilolux (*a*) values. The *b*/*a* ratios were obtained (*c*) for each chamber. The 16.2×klx should be a good factor to use in obtaining microeinstein values for these high-intensity lamps.

[5] Data were taken after 3 mm of water was added to the water bath in chamber 1.

chamber relative humidities (tests 1–3, table 10). The data suggest that steam additions can be made for control of humidity without affecting chamber temperatures. Comparisons with and without water in the water bath (tests 3 and 4, table 10) show that the special glass heat shield on the lamp reflectors removes the radiant energy. The slight increase in the chamber center temperature is probably because of higher reflected light.

The chambers were set up to determine maximum chamber temperatures. The plenum heaters were set for continuous operation and the exposure chamber room was set at about 77° F (25° C). The results (test 5, table 10) show that a chamber temperature of about 95° F (35° C) could be controlled using the proportional heater controls. The 1.1° to 1.7° C higher chamber center temperature (above exhaust) reflects radiant energy from the lamp on the thermocouples (even though they were shaded with the white cup reflectors).

The results show that exposure-chamber temperatures can be controlled between 65° and 95° F (18.3° to 35° C) and from about 40 to 90 percent relative humidity. At the higher temperatures, the system will permit lower relative humidities. These values are consistent with variations found in the eastern United States during much of the growing season.

Light intensities

The high-gloss white-enamel aluminum covering for each chamber increased the maximum light intensity (up to 25 percent) and improved light distribution within each chamber. There was little variation within chambers (table 11) except for the center (position 5) at the 30- and 60-cm heights (18- and 7-percent increase, respectively). There was considerable variability at 120 cm and a shadow at position 5 (43-percent reduction from other positions). All positions at 90 cm were uniform. The data in table 11 show that chambers 1 and 3 had higher intensities than chambers 2 and 4.

This difference reflected variation in lamp output and was corrected by the addition of a 7-in-diameter disk on the center of the lamp reflector shield for chamber 3 and a 6-in disk on the lamp reflector shield for chamber 1. The addition of the disks smoothed out the differences in the four chamber intensities (table 11, 60-cm height, comparison of position 5). Photosynthetically active radiation (PAR) in microeinsteins ($m^{-2}s^{-1}$) was compared with kilolux measurements for position 5 at the 90-cm height (table 11). A factor of 16.2 was found across the chambers for converting kilolux to microeinsteins and should be useful with the multivapor lamps. When 3 mm of water was added to the water bath over chamber 1, the chamber light intensities were not affected (table 11). For routine exposures, the disks are used for chambers 1 and 3, but the water baths are not used.

Plant studies

Bush snap beans (*Phaseolus vulgaris* L. 'BBL–290' and 'BBL–274') were used to determine the uniformity of injury within and across the four-chamber system. Seeds were planted in 5-cm Styrofoam cups containing a 2:1 (v/v) mixture of gravel and buffered Redi-Earth. Plants were thinned to one per cup at 5 d after seeding and transplanted to 10-cm pots at 7 d. Plants were watered daily with the Phytotron nutrient solution (Downs and Bonaminio 1976). Plants were grown under 26°/22° C day/night temperatures with a 9-h photoperiod at 40 klx and 60/80 percent day/night relative humidities. Plants were exposed at 26° C, 70 percent relative humidity, and about 36 klx light intensity to 0.40 μl/l O_3 for 3 h when they had two well-developed trifoliate leaves (21 d from seed).

Two experimental designs were run with all four chambers and five positions within the chambers. In experiment 1, both cultivars were used, but they were exposed on different days ('BBL–290' on the first day and 'BBL–274' the second day). Each exposure was replicated by morning and afternoon exposures. The entire design used 80 plants. The second design was a repeat of the first, but only 'BBL–290' was used (total of 40 plants). Percentage of foliar injury was determined (a 0–100-percent subjective index in 5-percent increments) 3 d after exposure for each expanded leaf on each test plant.

Injury was uniform across the test leaves and was not severe enough to suggest deleting any of the data. The average injury across the two primary leaves and the first three trifoliate leaves was used to test the positional and chamber effects in experiment 1 [even though the third trifoliate leaf in 'BBL–290' was not expanded (showed no injury)]. In experiment 2, the two

Table 12.—Uniformity of foliar injury to snap beans from ozone within and across chambers, Phytotron CSTR system[1]

Test factors	Plant injury (%)[2]	
	Experiment 1	Experiment 2
Position:[3]		
Probability >*F*	0.26	0.23
Mean (% injury $\pm S_{\bar{x}}$)	27.0±1.1	15.0±1.7
Min–Max (% injury)	24.6–30.5	10.7–20.3
Chambers:[4]		
Probability >*F*	.03	.65
LSD at 0.05	5.6	...
Mean (% injury $\pm S_{\bar{x}}$)	27.0±1.8	15.1±1.0
Min–Max (% injury)	23.2–31.9	13.4–17.6
Cultivar:[5]		
'BBL–290'	34.1	...
'BBL–274'	19.8	...
LSD at 0.05	3.9	...
Replication:		
Morning	25.5	19.1
Afternoon	28.4	11.0
LSD at 0.05	([6])	5.9

[1] Plants were exposed to 0.40 μl/l O_3 for 3 h at 26° C, 70 percent relative humidity, and about 36 klx of light. Experiment 1 used both 'BBL–290' and 'BBL–274', and experiment 2 used only 'BBL–290'.

[2] No interactions were found, and so the data are averaged across each experimental design. Data are average injury for the plant.

[3] The 5 positions used were the same as in table 1.

[4] The significant chamber effect for experiment 1 is associated with the afternoon (replication 2) exposure of 'BBL–290'.

[5] The averages shown include 5 leaves for each cultivar. Because 'BBL–290' did not have the 3d trifoliate, the average of 4 leaves should have been used. This average for 'BBL–290' and 'BBL–274' was 43 and 18 percent respectively.

[6] Not significant.

primary and first two trifoliate leaves were averaged.

There were no interactions in either experimental design for average plant injury. Each factor was considered separately within each experiment and across the other factors. The results (table 12) show no positional effects but do suggest a chamber effect in experiment 1. In this experiment, chamber 3 showed significantly more injury that was related to the afternoon replication for 'BBL–290'. When the concentration recording for this exposure was reviewed, we found that chamber 3 was consistently 0.03 to 0.05 μl/l above the other chambers for the first 60 min. This level, with the higher intensity light (table 11) for chamber 3, probably caused the increased injury. The chamber effect was not found in 'BBL–274' or in experiment 2 with 'BBL–290'. There were no positional or chamber effects for individual leaves, other than those associated with chamber 3, discussed above. The chambers function well as a CSTR, and there are no differences across the test chambers.

We included the data (table 12) for cultivars to show the difference in sensitivity between the two cultivars. We have chosen 'BBL–290' as a more sensitive cultivar and 'BBL–274' as a more tolerant cultivar for some of our work in the Phytotron. The results in table 12 show that these cultivars are well chosen. We often find a replication effect when the replications are morning and afternoon exposures. The results in table 12 show no replication effect, thus no day effect, for experiment 1, but a day effect for experiment 2. In this experiment, plants were more sensitive in the morning than in the afternoon.

DISCUSSION

Performance data compiled from the greenhouse and Phytotron CSTR systems show that both exposure facilities operate satisfactorily and that the chambers function as CSTR's. Both systems exhibit a high degree of shared-time component-sampling efficiency and dependability, good chamber pollutant control and distribution, and generally uniform temperature and light intensity within chambers. Both systems permit the researcher to have confidence in the uniformity with which plants respond to given gases across chambers, within chambers, and over time. Variances in response will primarily be environmentally induced differences across chambers and over time in the greenhouse system.

Gas-flow settings are fairly consistent for any specific chamber concentration but vary, especially in the greenhouse system, with light, temperature, and humidity within the greenhouse.

Plant growth and response to test chemicals may, in certain instances, depend upon the particular exposure chamber in the greenhouse system, probably as a result of environmental variations. Chronic or multiple-exposure studies should employ plant rotation between chambers, and rotation within a chamber may be used even though no significant within-chamber variations were found.

The system is amendable to complete dispensing and sampling automation and control. However, within the basic operational modes and experimental designs that we are presently employing, further automation will not be beneficial. For long-term chronic studies and unattended exposures, dispensing and sampling automation should be considered. The researcher should review his objectives and decide which variables to monitor. Temperature, light, and humidity should be routinely monitored because they affect the response of the plant to gaseous contaminants.

In addition to O_3, SO_2, and NO_2, the systems discussed here have been adapted for use to study the effects of HCl, Al_2O_3, acetic acid, toluene, xylene, aniline, and several other organic chemicals. The shared-time gas-monitoring unit has not been used for these chemicals, because no analytical instrument is available for most of the above compounds and because HCl adsorbs and desorbs too much on the sampling system for the HCl monitor (Geomet) to function in the shared-time format. All of these chemicals, except HCl, have been dispensed by means of the syringe-pump technique (fig. 3).

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APPENDIX.—MATERIALS AND COSTS FOR THE CSTR CHAMBER SYSTEMS

Materials and costs are presented for the construction of the four-chamber system used in the Phytotron and the nine-chamber system used in the greenhouse. Cost estimates are to the next higher $5.00 for components under $100.00 and to the next higher $25.00 for components over $100.00. Component costs are for guidance only and reflect January 1978 costs. Costs of construction are estimates.

Table A–1.—Materials and costs

Item	Phytotron		Greenhouse	
	Number	Cost ($)	Number	Cost ($)
CHAMBERS				
Chamber frame with door, constructed of hot-rolled steel strip (1-, 1½-, 2-in) and angle iron (1½-, 2-in), ⅛-in-thick; transmission holder; impeller assembly (shop constructed):				
32-in-wide by 54-in-high	4	125	...	...
42-in-wide by 48-in-high	...	...	9	275
Transmission, gear-drive, ⅓-hp (Anglgear, Plessey Industries):				
Model R–3000	2	100	2	100
Model R–3100	3	150	7	350
Epoxy paint (Glidden):				
Primer, chromate (gal)	1	20	2	40
White (gal)	1	20	2	40
Impeller motor:				
¼-hp, 115-V-a.c., 135-r/min (Dayton, model 6K354)	1	100	...	...
⅓-hp, 115-V-a.c., 1,725-r/min (Dayton, model 6K005)	...	...	1	60
Right-angle speed reducer (mated with ⅓-hp impeller motor), ⅓-hp, 115-r/min-output, 5-to-1-ratio (Winsmith, model M 133T)	...	...	1	90
3-Piece flexible coupling set for motor and transmission linkages, 7/16-in-bore (Lovejoy, model AL050)	9	10	18	20
Teflon FEP fluorocarbon film (both sides cementable): 3-mil-thick, 48-in-wide, 180-ft roll at $400 (Du Pont, type 300C20) (ft)	55	125	125	275
Starting collar, galvanized 30-gage, for inlet air duct:				
3-in	4	5	...	...
4-in	...	...	9	5
Door butt hinges, 2- by 2-in, steel (pair)	4	5	18	15
Door fasteners (National Mfg., Sterling, Ill., model V750RM) (pair)	4	15	9	30
Plywood, ¾-in, AC, exterior-grade, for chamber base: 4- by 8-ft sheet	2	30	...	...

Table A–1.—Materials and costs—Continued

Item	Phytotron		Greenhouse	
	Number	Cost ($)	Number	Cost ($)
CHAMBERS—continued				
Plywood, 5/8-in, AC, exterior-grade, for chamber base: 4- by 8-ft sheet	...	...	5	60
Silicon calking, translucent, construction-grade: 12-oz cartridge (General Electric, No. 1201)	2	10	3	15
Chamber clamp [stainless-steel strip, about 25-mil-thick by 7/8-in-wide, with a radiator clamp (cut in half) welded to each end (to secure Teflon film to chamber)]	12	40	18	60
Aluminum channel, 45-in-long, 3/4-in-wide (for vertical Teflon film support) (pieces)	8	5	18	10
Open-cell vinyl foam, 1/2-in-thick by 3/4-in-wide (for use with chamber clamps in securing Teflon film) (ft)	150	15	200	20
Closed-cell vinyl foam, 3/8-in-thick by 1/2-in-wide (for door gaskets) (ft)	75	10	160	20
Aluminum sheet metal, high-gloss white-enamel, 30-gage: 5- by 8-ft sheet (for use as chamber side covering)	4	40	...	...
Insulation, rubber, 1/2-in-thick: 3- by 4-ft sheet (Rubatex)	16	160	...	...
Insulation adhesive (Rubatex) (gal)	1	10	...	...
Chamber exhaust duct, aluminum, 2-in-o.d. by 1 7/8-in-i.d. (ft)	4	5	18	5
Exhaust-duct flow-control valve:				
Ball valve, 1 1/2-in, PVCI, with Viton o-ring seal (Chemtrol, part No. 21599011)	4	150	...	...
Butterfly valve, 2-in, cast-iron (Weco, FMC Corporation, model 12)	...	...	9	375
CHAMBER INLET				
Filter, particulate fiberglass (Fram):				
18- by 18- by 1-in-thick	2	5	...	...
24- by 24- by 2-in-thick	...	...	1	5
Filter, activated charcoal:				
24- by 24- by 12-in-deep (Fram, model RT 50–375)	...	...	1	175
18- by 18- by 1-in-thick (Barnebey Cheney)	2	30	...	...
Filter housing:				
18- by 18- by 4-in-deep: 26-gage galvanized sheet metal (shop fabricated)	2	30	...	...
24- by 24-in transition to 6-in pipe: 26-gage galvanized sheet metal (shop fabricated)	...	...	1	20
Stovepipe and pipe fittings, galvanized, 30-gage (for manifolds):				
Starting collar, 4-in	2	15	...	...
Tee, 4-in	4		...	...
Elbow, 4-in	...	...	9	10
Starting collar, 4-in	...	...	6	
Round pipe, 4-in: 5-ft length	4	10	...	...
Reducer, 6- to 4-in tapered	...	...	9	20
Round Pipe, 6-in: 5-ft length	...	...	8	25
Tee, 6-in	...	...	11	40
Tee-joint, 6-in	...	...	4	10
Elbow, 6-in	...	...	2	
Starting collar, 6-in	...	...	4	

Table A–1.—Materials and costs—Continued

Item	Phytotron		Greenhouse	
	Number	Cost ($)	Number	Cost ($)
CHAMBER INLET—continued				
Clamp, hose, radiator, stainless-steel, 4-in	12	5	...	...
Hose, dryer vent, PVC, flexible, 4-in (ft)	40	25	...	...
Insulation, rubber, ½-in-thick: 3- by 4-ft sheet (Rubatex)	...	...	12	120
Adhesive, insulation (Rubatex) (gal)	...	...	1	10
Inlet duct:				
Stovepipe and pipe fittings, galvanized, 30-gage:				
Starting collar, 3-in	4	5	...	...
Starting collar, 4-in	...	...	9	5
Elbow, 4-in	...	...	9	10
Round pipe, 4-in: 5-ft length	...	...	9	20
Pipe and pipe fittings, stainless-steel, 26-gage (McMaster-Carr, part No. 1767N):				
Round pipe, 3-in: 2-ft length	10	80	...	...
Elbow, 3-in	8	50	...	...
Insulation, pipe: 6-ft length (Rubatex):				
3⅛-in	4	20	...	...
4⅛-in	...	...	9	50
Steam supply:				
Valve, solenoid, 3-way, 120-V-a.c., with 0.093-in ports, ¼-in pipe connection, stainless-steel body (ITT General Controls, model K273FA3322)	4	80	...	...
Valve, flow-control, metering, brass, 3°-stem, 0.047-in-orifice, 18-turn, with ¼-in Swagelok connections (Hoke, model 1325G4B)	4	150	...	...
Plenum box:				
Box fabricated of 22-gage galvanized sheet metal, 21- by 11- by 28-in-deep (includes 3 inner baffles)	4	35	...	...
Heater:				
500-W, finned, 120-V-a.c. strip heater (Chromalox, model PTF–18)	4	75	...	...
750-W, finned, 120-V-a.c., strip heater (Chromalox, model SFTS–1641–F)	4	100	...	...
Cooling coil, evaporator, turbulator (Warren-Sherer, CEL 255–6)	4	125	...	...
Valve, coolant-flow, gate, ½-in	4	25	...	...
Temperature controller (thermostat), 55°- to 85°-F, solid-state (Barber-Coleman, model TP–8101)	4	150	...	...
Electric heat controller, heater-driver (Barber-Coleman, model CP–8425–120–0–1)	4	750	...	...
Temperature limit switch, electrical, 250°-F	4	15	...	...
Blower, recirculating, 54-ft^3/min free-air, shaded-pole (Dayton, model 4C012)	4	50	...	...
Hose, dryer vent, PVC, flexible, 3-in (ft)	10	5	...	...
Starting collar, galvanized, 30-gage:				
3-in	12	10	...	...
4-in	4		...	...
Insulation, rubber, ½-in-thick: 3- by 4-ft sheet (Rubatex)	6	60	...	...

Table A–1.—Materials and costs—Continued

Item	Phytotron		Greenhouse	
	Number	Cost ($)	Number	Cost ($)
CHAMBER EXHAUST				
Hose, exhaust, 2-in-neoprene, flexible	12	25	...	...
Filter, activated-charcoal, 500-ft^3/min, 12- by 24- by 8¾-in-deep (Barnebey-Cheney, model FND)	1	175	...	...
Filter, activated-charcoal, 1,000-ft^3/min, 24- by 24- by 12-in-deep (Fram, model RT50–375)	...	...	1	175
Blower, high-pressure, direct-drive, 335-ft^3/min at 4 in water static pressure, 9-in-diameter, ⅓-hp, 115-V-a.c. (Dayton, model 7C504)	1	85	...	...
Blower, high-pressure, direct-drive, 810-ft^3/min at 1 in water static pressure, 10⅝-in-diameter, 1-hp, 208-V-a.c., 3-phase (Dayton, model 7C741)	...	...	1	125
Hose, dryer vent, PVC, flexible, 4-in (ft)	8	5	...	...
Clamp, hose, radiator, stainless-steel, 4-in	6	5	...	...
Pipe and pite fittings, PVC, Sch. 40:				
Pipe:				
1½-in (ft)	8	25	...	...
3-in (ft)	40		...	...
Tee, 3-in	5	25	...	...
Elbow, 3-in	1	5	...	...
End cap, 3-in	2	5	...	...
Bushing, reducer, 3- to 1½-in	4	5	...	...
Stove pipe and pipe fittings, galvanized, 30-gage:				
Pipe, 6-in (ft)	45	25	...	...
Starting collar:				
4-in	4	5	...	...
6-in	...	...	3	5
Tee, 6-in	...	...	1	5
Elbow, 6-in	...	...	1	
End cap, 6-in	...	...	2	5
DISPENSING UNIT				
Rotameter, glass plus carboloy ball float (0–90.9 cm^3/min + 0–453.5 cm^3/min), with integral needle control valve (Brooks Instrument Division, Sho-Rate "150," model 1355–8506)	12	2,100	27	4,800
Compressor, air, 115-V-a.c., with stainless-steel bellows, (Metal Bellows Corporation):				
¼-hp, 1.4-ft^3/min-output free-air (model MB–151)	1	250	...	...
¼-hp, 2.75-ft^3/min-output free-air (model MB–302)	...	...	1	375
1/40-hp, 0.4-ft^3/min-output free-air (model MB–41)	...	...	1	150
Rotameter, air, brass, 0.6–5.0-l/min, "Visi-float" (Dwyer Instruments, Inc., model VFA–BV–23)	13	200	28	425
Manifold, aluminum, with ¼-in-thick wall (shop constructed):				
Air:				
4- by 18½-in	1	25	...	...
4- by 36-in	...	...	1	35
Ozone, sulfur dioxide, and nitrogen dioxide:				
4- by 6½-in	3	45	...	...
4- by 8-in	...	...	3	45

Table A–1.—Materials and costs—Continued

Item	Phytotron		Greenhouse	
	Number	Cost ($)	Number	Cost ($)
DISPENSING UNIT—continued				
Generator, ozone:				
Electric-discharge (shop constructed): chassis approximately 10 by 7 by 7 in, output approximately 0.02 g/h with oxygen parent gas	1	120	...	...
Electric-discharge: maximum output approximately 6 g/h with oxygen parent gas (2% weight concentration) (Welsbach Ozone Corporation, model T–23)	...	...	1	1,500
Bubbler, constant-pressure glass-reservoir, Pyrex (glass-shop fabricated):				
2- by 18-in	1	40	...	...
2- by 30-in	...	...	1	50
Valve, flow-control, needle, 0.172-in-orifice, 3-turn, brass, with ¼-in-Swagelok connections (mated with glass reservoir) (Whitey, model B–1RS4)	1	20	1	20
Rack, dispensing, slotted steel-angle (2¼- by 1½-in), 14-gage:				
6- by 1- by 1½-ft, with 3-in casters	1	45	...	...
6- by 2- by 1½-ft, with 3-in casters	...	...	1	50
Fittings, tube, compression, assorted, aluminum and 316 stainless-steel, ⅛-in and ¼-in (Swagelok)	100	350	175	625
Tube, dispensing, flexible, Teflon (TFE), ¼-in-o.d. by 3/16-in-i.d. [used for supply to chambers and dispenser construction (Comco, Commercial Plastics & Supply Corp.)] (ft)	450	275	775	475
SAMPLING UNIT				
Tube, sampling, flexible, Teflon (TFE), ¼-in-o.d. by 3/16-in-i.d. [used for sample lines from chambers and associated sampling system) (Comco, Commercial Plastics & Supply Corp.)] (ft)	300	200	550	350
Heat tape, flexible, 5-W/ft, continuous, ¾-in-wide [nonthermostat (McMaster-Carr)]:				
3-ft roll (No. 3564K11)	4	10	...	...
6-ft roll (No. 3564K12)	6	20	...	...
45-ft roll (No. 356K17)	1	10	...	...
Insulation, sampling-line (McMaster-Carr):				
Pipe, ¼-in-i.d. (nominal) by ⅜-in-thick, Cell-o-Flex: 6-ft length (No. 4464 N21)	2	5	...	...
Pipe wrap, fiberglass, 3-in-wide: 50-ft roll	2	5	...	...
Valve, solenoid, 3-way, with stainless-steel body, Viton seats and o-rings, 3/32-in orifice, ¼-in NPT connections, 24-V-d.c. coil (Versa, model ESM–8302–66–H)	8	175	18	375
Fittings, tube, compression, 316 stainless-steel, ⅛-in and ¼-in nylon ferrules (Swagelok)	70	250	100	350
Manifold, exhaust, aluminum, with ¼-in-thick wall (shop constructed):				
4- by 6½-in	1	15	...	...
4- by 12-in	...	...	1	20
Manifold, sampling, clear-glass (Pyrex), with ball flask with sixteen ¼-in Sovirel Teflon washer fittings; volume approximately 250 ml (glass-shop fabricated)	1	150	1	150

Table A–1.—Materials and costs—Continued

Item	Phytotron		Greenhouse	
	Number	Cost ($)	Number	Cost ($)
SAMPLING UNIT—continued				
Rotameter, brass, 0.6–5.0-l/min, with "Visi-Float" (Dwyer Instrument, Inc., model VFA–BV–23):				
Exhaust, sample	8	175	...	...
Sample (flow-through sampling manifold)	1	20	...	...
Pump, vacuum, ¼-hp, 115-V-a.c., with stainless-steel bellows (Metal Bellows Corporation):				
1.4-ft^3/min-output free-air (model MB–151)	1	250	...	...
2.75-ft^3/min-output free-air (model MB–302)	...	...	1	375
Scanner, 24-V-d.c.-output, with electromechanical stepper, programable channel selection, automatic and manual advance (shop constructed):				
8-point	1	125	...	...
20-point	...	...	1	200
LIGHTS				
Assembly, light, metal halide, with ballast and reflector [Filterglow—facet reflector surface, indoor (General Electric)]:				
1,000-W, 277-V-a.c. (No. C774G105)	4	900	...	...
400-W, 120-V-a.c. (No. C773G127)	...	...	9	1,350
Connecter cable, remote-power, ballast-to-reflector, 10-ft-long (General Electric No. C740G263)	...	...	9	325
Bulb, metal arc (GTE Sylvania):				
1,000-W (No. M1000/BU–HOR)	4	150	...	...
400-W (No. M400/BU–HOR)	...	...	9	125
Water bath, 32-in-wide by 4-in-high, clear Plexiglas (⅛-in-thick sides by ¼-in-thick base); aluminum legs for support upon chambers (shop fabricated)	4	250	...	...
INSTRUMENTATION				
Ozone monitor, 0–5-µl/l (Monitor Labs, model 8410)	1	3,100	1	3,100
Ethylene converter, ozone monitor (shop fabricated)	1	150	...	...
Nitrogen dioxide monitor, 0–5-µl/l (Monitor Labs, model 8440)	1	5,000	1	5,000
Sulfur analyzer, 0–10-µl/l (Meloy Laboratories, model SA 160–2	1	5,000	1	5,000
Dewpoint analyzer, 40°- to 128°-F (E G & G Environmental Equipment Division, model 880)	1	2,600	1	2,600
Recorder, temperature, Speedomax "W", thermocouple, type T, 30°- to 150°-F, 24-point, 10-in, with flexelect B point selection" (Leeds & Northrup No. 524–101–000–1317–6–602–521–522–526–378–315)	1	2,200	1	2,200
Recorder, millivolt, strip-chart, 10-in, single-pen, linear servomotor (Hewlett Packard, model 7123A):				
0–50-mV	1	1,600	1	1,600
0–100-mV	3	4,800	3	4,800

Table A–2.—Installation and fabrication times and costs[1]

Section	Phytotron		Greenhouse	
	Time (h)	Cost ($)	Time (h)	Cost ($)
Chambers	54	270	72	360
Chamber inlet	40	200	16	80
Chamber exhaust	8	40	16	80
Dispensing unit	24	120	64	320
Sampling unit	40	200	72	360
Lights	8	40	16	80
Instrumentation	8	40	6	30
Total	182	910	262	1,310

[1] Labor at $5.00/h.

Table A–3.—Cost summary

[Dollars]

Section	Phytotron	Greenhouse
Chambers	1,150	1,865
Chamber inlet	1,905	520
Chamber exhaust	390	315
Dispensing unit	3,470	8,550
Sampling unit	1,410	1,640
Lights	1,300	1,800
Instrumentation	24,450	24,300
Installation and fabrication ($5/h)	910	1,310
Total	34,985	40,300

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